

BEACH CUSPS OF
MONTEREY BAY, CALIFORNIA

CHRONOLOGICAL

JOHN LYLE BRUEGGEMAN

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THESIS

BEACH CUSPS OF MONTEREY BAY, CALIFORNIA

by

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Thesis Advisor:

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June 1971

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Beach Cusps of Monterey Bay, California

by

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Lieutenant Commander, United States Navy
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ABSTRACT

A radiographic study was conducted on impregnated sand samples taken from beach cusps on Marina Beach, Monterey Bay, California, over a 7-month period from September 1970 to April 1971. The radiographs revealed much more structure than is discernable with the unaided eye in trenching or peeling. The microstructure found consisted of cross-lamination, rhythmic stratification, and distinct mineral layering. Migration of these cusps was studied by means of visual observations and time-lapse photography. Cyclic changes in the cusp profile were found to correspond with wave action and tidal influences. No simple relation between ocean action and cusp structure or development was evident.

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I. INTRODUCTION

A. GENERAL

Beach cusps are periodical, crescent-shaped formations of sedimentary material ranging from fine sand to 3-ft boulders. They are formed in the foreshore region between the shoreline and the berm. A "cusp" or "cusate formation" refers to one of a series of naturally occurring mounds of beach material separated by crescent-shaped troughs (Fig. 1). Cusps are spaced at more or less regular intervals along the beach face. The seaward extension is known as the "apex" or "horn". The curved or depressed region is referred to as the "furrow", "swale" or "trough". Beach cusps are among the most frequently observed phenomena on beaches along seas, lakes and rivers.

The beach cusps with which this investigation deals are of the type evolved on a sandy ocean beach. These particular cusps are believed to represent erosion of the beach face as opposed to the deposition of material in the form of a cusp.

B. PURPOSE AND SCOPE

The research described in this paper deals with the sedimentary structure and the movement of beach cusps on Marina Beach in the middle portion of Monterey Bay, California (Fig. 2). The primary purpose of the study was to examine the microstructure of beach cusps by radiographic

analysis. Previous investigations in this area have dealt with structural features readily observed by the unaided eye. The secondary purpose of the study was to perform a visual and photographic study of the movement and profile changes of a typical beach cusp.

The scope of the investigation was limited to sand cusps on a 1,000 m section of beach considered typical of mid-southern Monterey Bay. Data collection was conducted from Sept 1970 through April 1971.

C. AREA CHARACTERISTICS

The southern portion of the Monterey Bay coast is characterized by a long, continuous sand beach, 14 miles in length, extending from Moss Landing at the head of the Monterey Submarine Canyon to the Monterey Harbor at the extreme southern end of the bay (Fig. 3). The southern portion approximates a logarithmic spiral observed on other beaches protected by headlands [Yasso, 1964]. The fore-shore slope ranges from moderate (1:12) at the northern end to gentle (1:20) at the southern end. Beach texture ranges from coarse sand in the north to fine sand in the south and is composed mainly of quartz and feldspar. Bordering the beach is a Quaternary dune field which forms the shoreline on this section of coast (Fig. 4, 5 and 6).

The headland west of the City of Monterey protects the southern portion of the beach from storm-wave attack. Wave refraction results in a negligible breaker angle along the

entire beach most of the time. General longshore currents and littoral transport are small [Brennan and Meaux, 1964; Dorman, 1968]. Localized, periodic and regularly spaced rip cells are common from the Salinas River to the southern end of Fort Ord (Fig. 5). The beach profile has been found to be very dynamic and is a function of daily and seasonal changes in the wave and tide regimes [Koehr and Rohrbough, 1964; Harlett, 1967].

The area of study was located between two commercial sand extraction sites or sand mines (Fig. 4 through 8). The sand mines use a large "V-shaped" scoop operated by a drag line to remove sand from the swash zone, and have been operating for over 20 years in this area. The southern mine is in operation but the northern one closed approximately 6 months before this study commenced. Their operation appears to have had no effect on the general beach zone features, and cusps have been observed migrating through the scraped areas.

The cusps are semi-permanent features in this area throughout the year and form a continuous sequence. Two distinct types of cusps are present; beach cusps whose sizes range from 8 to 25 m from horn to horn, and giant cusps that measure approximately 1000 m from horn to horn (Fig. 4 through 8). The smaller beach cusps occur in groups between the horns of the larger cusps.

D. PREVIOUS WORK

1. Beach Cusps

Previous studies of beach cusps date from 1834 when Palmer described curious ridges and furrows on a shingle beach in England [Johnson, 1919]. Johnson gave an extensive summary of previously published material concerning cusps in his classic monograph on shores. He described various cusp types and formulated the theory that cusps were formed by selective erosion of the swash scouring on random depressions. Johnson considered cusp spacing to be roughly proportional to wave size. Shepard [1935] suggested that cusp formation might be attributed to waves acting in the absence of large tide ranges. He found that cusp destruction at Santa Monica, California, followed a definite 2-week cycle corresponding to neap and spring tides. The cusps were buried during large tidal ranges and reappeared during small ranges.

Wave tank experiments on cusp development [Escher, 1937] produced cusps by the action of ordinary waves combined with standing waves, the latter propagating at right angles to the beach. Johnson and Timmermans [Escher, 1937] produced small cusps in wave tank experiments which were later classified as isolated phenomena not directly associated with the larger cusped formations.

Butler [1937] found boulder beach cusps on Lake Olga, Quebec, which were not related to tidal effects. Butler concluded, in support of Shepard's findings, that tides were not necessary for the development of cusps. In another

study of lake cusps, Evans [1938, 1939] supported Butler and Shepard in their theory of wave-formed cusps. Evans classified cusps into five distinct categories of which the first four are normally reserved for lake studies only. The fifth category concerns the "ideal cusps", as he called them, which are normally dealt with in general coastal studies. He found that cusps were not necessarily equidistant and varied from 40 to 100% in their spacing intervals.

Bagnold [1940] referred to hollows and ridges found on an Egyptian beach where lack of a significant tide associated with steady onshore winds apparently accounted for their development. Although he never referred to the formations as cusps, his diagrams and descriptions can be interpreted as cusped formations.

Krumbein [1944], in a study of shore processes in Halfmoon Bay, California, suggested that cusp length was a function of average wave and tide conditions. He noted that cusp length decreased systematically from south to north along the beach. Halfmoon Bay is shaped in the form of a logarithmic spiral as is southern Monterey Bay, and this size gradation of cusps may be related to the shape of the bay [Yasso, 1964].

Evans [1945], after extensive observations, concluded that cusps form by the process of periodic erosion of a ridge-like obstruction or berm by wave action. The berm is supposedly breached with subsequent cusping formed by parabolic motion of water in the swash zone. He conceded

that not all cusps were formed in this manner and suggested that several cause-and-effect conditions resulted in cusp development. Kuenen [1948] postulated that the wave swash erodes depressions and is deflected laterally to form the horns of cusps.

Kuenen observed that the horns of the cusps often are of coarse material and the depressions consist of finer material. This has since been further verified in tank experiments [Flemming, 1964].

Twenhofel [1950] noted that it was not certain that beach cusps have been recognized in the geologic column, but that certain features which have been observed in sandstone resemble them. Since cusps are shore features, he questioned why cusps were not destroyed as the seas advanced or by subaerial erosion as the seas retreated. His question remains unanswered.

Schupp [1953], in a study of the cobble cusps on the beach off Santa Monica, California, found a good correlation between periods of neap tides and cusp formation and between periods of spring tides and cusp disintegration. His study remains one of the most complete investigations yet conducted.

Trask [1956] at Point Reyes Beach, California, found cusp length and profile varied with sediment grain size and that cusps were superimposed on larger super cusps 1500 to 3000 ft in length. He noted cusp migration and cut and fill, but offered no explanation as to why they were taking place.

Trask provided the first published field study which included adequate data for cusp formation or movement analysis.

A correlation between cusp spacing and width of the swash zone was found to exist by Longuet-Higgins and Parkin [1962]. From extensive field work as well as exhaustive wave-tank experiments associated with cusps, they concluded that; (1) the swash zone width is more important than wave height or wave period in cusp spacing, and (2) excessively high wave activity destroys the cusps.

Shepard [1963] reviewed the literature on cusp-like coastal features and related for the first time the full spectrum of cusped formations. He described cusps ranging from small beach cusps (several feet in length) to cusped forelands such as Cape Kennedy. Cusplike features of even a smaller scale were described by Allen [1968] as cusped ripples.

Zenkovich [1967] provided the first account of work done by Russian investigators in the field of cusps. The similarity of their findings to those of Western scientists further substantiates or supports many of the aforementioned theories. Zenkovich suggested that coastal defenses such as seawalls and breakwaters might well include cusplike design to dissipate energy more efficiently.

More recent extensive field observations have provided a plethora of cusp descriptions but no complete theory of cusp origin. Russell and McIntire [1965] studied the flow patterns of water during cusp formation (Fig. 9). The

flow of swash and backwash was believed related to cusp formation but no definitive answer was evident. An interesting theory proposed during this period was that cusps were formed by an extension of Plateau's Rule [Cloud, 1966]. Plateau's Rule involves what happens to a liquid cylinder under gravity-free conditions when its length exceeds its circumference. Plateau found under these conditions that the liquid cylinder became unstable and separated into subequal divisions whose lengths were proportional to the diameter of the cylinder. Cloud postulates that the cylindrical form of a breaking wave may wash up onto the beach in semi-regular "jets" or fans and may result in cusp formation. No evidence was forthcoming to support this theory.

Dolan and Ferm [1968] proposed an extension of Shepard's description of a full range of cusped features. They hypothesized that the Gulf Stream eddies result in cusped forelands with lesser cusped features forming between them by some as yet unknown cause. Dolan and Ferm proposed that cusped features on coasts tend to have a hierarchical arrangement in terms of length from horn to horn, and classified cusped features as follows; (1) cusplets (1.5 m), (2) beach cusps (8 to 25 m), (3) storm cusps (70 to 120 m), (4) shoreline rhythms or giant cusps (700 to 1500 m), (5) secondary capes (10^4 m), and (6) primary capes (10^5 m). Two still larger classifications were extrapolated from what appeared to be a logarithmic spacing scheme, but their existence is uncertain.

In two non-cusp oriented studies Boisvert [1966] and Pickett [1967], while investigating the Gulf Stream, arrived at two figures for eddy diameters which correlate exactly with the horn-to-horn dimensions of Dolan and Ferm's primary Atlantic Coast capes and the next larger cusplate feature. Boisvert determined that Gulf Stream eddies average 50 miles across, a width which compares nicely with the 10^5 m dimension for primary capes. Pickett arrived at the figure of 534 miles for the length of Gulf Stream meanders, which corresponds with the next larger cusp dimension of Dolan and Ferm. Since most investigators agree that the smaller cusp features do not form when longshore currents are present, the author believes there may be a transition zone in the rhythmic or giant cusp range where major ocean current features become important factors in cusplate formation. Dolan and Ferm's presentation raises two central questions regarding the origin of cusplate features; (1) are they controlled by the interplay of ocean currents with shoaling and breaking waves, and (2) are the interacting processes continuous in nature?

Bowen and Inman [1969] showed by theory and lab experiments that interference between ordinary incoming waves and edge waves produces a nearshore circulation of rip cells with which is associated the formation of beach cusps. This theory is associated with that of Longuet-Higgins and Parkin [1962] and seems to explain the formation of beach cusps in a more general and logical manner than any previous

theories, although it seems probable that it may not explain the cause of all beach cusps of ordinary size.

2. Beach Stratification

Many studies concerning beach stratification have been carried out during the last 100 years, but it was not until about 1937 that a definitive study was conducted to coalesce the data, descriptions and conflicting theories that had accumulated. Since that time numerous studies have followed. Many of these studies are not concerned with cusps and only those investigations felt applicable are included for background.

Thompson [1937], in a study of California beaches, described alternating light and dark beach laminations between 0.1 and 1.0 inches in thickness. He concluded that these laminae originated from a combination of waves of varying energy moving sediment of varying size and specific gravity. He noted that the depositional phase of lamination resulted from a combination of neap tides and varying wave energies, yet no rhythmic banding caused by tidal fluctuation alone was discernable in his trenching studies. Thompson described four distinct types of "cross-lamination" (Fig. 10) which he observed on uncusped beaches. He described these as zones from a few inches to 10 ft thick and from a few feet to 200 ft long. Duncan [1964] proposed that cross-lamination may result from deposition by flood tide swashes.

Kuenen [1950] divided stratified sediments into three distinct categories according to thickness. He defined

layers up to 1 cm in thickness as "laminae" and thicker layers as "beds". "Stratum" was defined as a thicker bed or a series of beds distinct from underlying or overlying beds. Although Kuenen dealt primarily with current bedding and offshore stratification in the geologic column, his terminology has been adopted in beach studies.

During this period the first microstructural study of laminated beach sand was conducted by Emery and Stevenson [1950]. Thin-sections of naturally and artificially cemented beach sands were used for a microscopic study of the size distribution of sand grains that form laminae in beaches. They found that the median diameters of sand in individual laminae range from much coarser to much finer than the median diameter of the entire sand sample.

Directly associated with the stratigraphic structure is the depth of sediment disturbance associated with waves and subsequent swash on the foreshore. King [1951, 1959] found a significant correlation between depth of disturbance, wave height and wave energy. The depth of disturbance was found to increase with increasing wave height and energy. Inman and Filloux [1960] proposed that the thickness of individual layering is indicative of the degree and intensity of erosion resulting from the associated wave energy.

Uneven laminae thickness in a sequence of laminae was found by Otvos [1965] to be associated with sediment distribution of a tidal period. Sediment distribution during a single tide is apparently influenced by the sediment

cover remaining from the previous tide. Otvos found that the degree of wave activity superimposed on the tides determines the texture of sand available for the next cycle to redistribute and laminate.

The possibility of differential packing of the sand across the beach as a function of wave and tide action was brought forth by Scott [1954] in wave tank experiments at the University of California. Scott found that the structure developed on the foreshore was tightly packed due to the amount of wave reworking of the surface during deposition. The berm deposition was not accompanied by reworking and, hence, the structure was loose. There apparently was a gradation of packing between the two regions.

On a micro-scale, Clifton [1968] described a dual lamination which he has observed in the upper swash zone consisting of a fine, heavy mineral dominated zone at the bottom of a given laminae grading to a coarse, lighter mineral region at the top. Dual lamination or the separation of coarse from fine and light from heavy grains during deposition was found to occur within a transported layer of sand in suspension immediately after erosion during backwash. Clifton found that sand is transported as a cloud of grains, and that the individual grain density determines whether a grain will settle to the bottom or stay in the upper portion of the laminae. Inman and Filloux [1960] observed that the heavy minerals settle at about the same

speed as the quartz grains, but both act quite differently when transported as bed load. Due to their usually smaller size and higher specific gravity, the heavy minerals move slower than the lighter minerals when the sand is in suspension in the swash.

II. PROCEDURE

A. COLLECTION OF FIELD SAMPLES AND DATA

Undisturbed and oriented sand samples for radiographic analysis were obtained using a Senckenberg sample box (Fig. 11). The method was first described by McMullen and Allen [1964] and uses impregnation techniques to obtain hardened impregnations of sedimentary structure for laboratory study.

Thirteen Senckenberg sample boxes were fabricated from 1/8-inch stainless steel sheet metal by the Machine Facility at the Naval Postgraduate School. Twelve boxes were used for sampling with one kept in reserve. Inside dimensions of the main body were: height, 8 inches; width, 6 inches; and depth, 3 inches. The dimensions of the box were suggested by Bouma [1969] and seem best suited for general sampling of unconsolidated sediments. For deeper sampling with the box a staircase technique could be employed with successive levels of boxes.

In the fabrication of the sample boxes fit on all sliding surfaces was maintained with a maximum of 1/32-inch tolerance. Because each box was individually fitted with its own sliding sides, it was mandatory that all three sections be numbered for matching. The numbering was accomplished by stamping the numbers on all three sections of each box. All lower cutting edges were ground to knife sharpness to minimize surface drag while pressing the box

into position. One edge of the bottom plate (Fig. 11) which was not sharpened was bent over to form a comfortable gripping surface for ease of placement.

The first step in using the box involved implanting the main body into the sampling area (Fig. 12). In the moderately coarse sand found on Marina Beach this was a simple matter of pressing in by hand except for the last inch of penetration which required one's foot or a mallet struck onto a board covering the entire upper surface of the box's main body. Next the side of the box was slid carefully into position (Fig. 13). The sand was then removed from the sliding face of the box using the bottom plate as a shovel (Fig. 14). Subsurface structure revealing macrolamination was evident at this stage (Fig. 15 and 16). Just enough sand was removed to expose the bottom of the box; then the bottom plate was inserted (Fig. 17). The box was then carefully removed, placed on its side, and a 1-inch wide rubber band cut from a 7.50-20 inner tube was placed around the box to hold it together for transport (Fig. 17).

Sampling with the boxes was accomplished by selecting the area of study, placing the boxes and establishing a level line for reference (Fig. 14 and 16). By measuring and recording vertical distances from each end of the boxes to the reference line and distances between boxes, their positions could be duplicated for the radiographic analysis phase. Visual estimates of wave height were also taken during the sample collection with a brief description of the previous 24-hour period weather.

After a group of boxes had been prepared they were transported to the Beach Laboratory at the Naval Postgraduate School. No deformation, packing or damage was incurred during transport except in one instance when a box was inadvertantly dropped, and even then the sample was still useable for comparison purposes. An open, unprotected area was selected behind the laboratory for impregnation since the process was messy and noxious (Fig. 18). At this point the sliding sides of the boxes were removed (Fig. 18), leaving the rubber bands in place to hold the bottom plates on during impregnation.

Impregnation of the sand samples was a vital step to the success of this study and the technique yielded permanently hardened, easily oriented, undisturbed sediment samples or "impregnations". Bouma [1969] described the technique of using liquid polyester resin to harden unconsolidated sediment into cemented blocks. After conferring with Dr. H. E. Clifton of the U. S. Geological Survey, Menlo Park, California, who had used the same technique in stratigraphic structure studies of the nearshore area [Clifton, 1971], it was decided that any marine polyester resin of the type used in fiberglass boat construction would produce the desired results. A resin with the trade name of "Sea Jay", whose characteristics are described in Appendix A, was procured from a local marine supply house. Prior to the purchase of resin, Elmer's Glue was tried experimentally and found to work quite well except that the impregnations were thin, subject

to water damage, and broke more easily than the resin impregnations. The glue could not be used in wet sand samples but the resin worked in all cases.

The method used in this study involved pouring resin over the top of the opened sand boxes (Fig. 19). After many tries it was found that 2 ml of hardener thoroughly mixed with 300 ml of resin produced 1- to 2-inch thick impregnations. The amount of hardener used determines how fast the resin sets up, which is the most critical factor in obtaining the desired thickness of impregnations. Too much hardener resulted in thin, easily fractured impregnations; too little hardener resulted in impregnations of variable thickness, often with the undesirable result of the complete box being impregnated, requiring up to 2 weeks to cure.

For best results two boxes were impregnated at a time with 150 ml of resin poured on each. While the initial 150 ml was penetrating the sand, another 300 ml batch was mixed and divided between the boxes. In this manner the resin did not run over the sides prior to its hardening. If the samples were allowed to set too long before addition of the second application it was found that globules of semi-hardened sand formed on the underside of the impregnations and poor results were obtained from the radiographic processing. It was found imperative that the boxes be level and that the resin be poured evenly for uniform impregnations.

Hardening time was found to be a function of air temperature and humidity, amount of direct sunlight, and the

amount of water in the sand samples. High air temperature (75-80 F), direct sunlight, low to medium air humidity and low sample water content resulted in a 12-hour curing time. Hardening times for lower temperatures, cloud cover, high air humidity and wet sand ranged up to 1 week. Several times it rained either during impregnation or immediately after with no apparent degradation of impregnation quality. An average of 2 days was allowed for curing and excellent results were obtained.

Once the samples were hardened they were labelled for identification and orientation purposes by spraying white paint on the top, smooth edge and either scratching or writing with a felt-tip pen the date and sample number on the painted surface.

To remove the hardened impregnations from the boxes, leather gloves were mandatory to prevent cutting of one's hands as the resin hardened into knife-sharp edges at the box boundaries. The rubber bands were removed and the bottom plates of the boxes were knocked off (Fig. 20). The loose, unimpregnated sand was then dumped out by gentle tapping and the impregnations removed by bending the sides of the boxes outwards (Fig. 21). The impregnations were gently tapped on a hard surface to dislodge loose or semi-loose sand grains. This last process usually revealed distinct ridges indicating variable depth of impregnation of individual laminae (Fig. 22 through 24).

The impregnations were then transported to the X-ray laboratory of the Naval Postgraduate School for radiographic analysis and photographing. Since the resin was generally not fully hardened on the ridged face, transport at this stage was done with the impregnations lying with their smooth faces down to avoid loss of structure. The X-ray machine used was a Norelco Searchray. Impregnations were placed smooth-face down oriented with the end originally at the beach surface nearest the lead letters used to identify the X-rays (Fig. 25). Uniform orientation throughout this process was vital for analysis. Impregnations were X-rayed individually (Fig. 26) as exposures varied for differing impregnation thickness. The X-ray machine was set at 5 mA, 30 kVA and the exposure time varied from approximately 15 sec for 1-inch impregnations to 35 sec for 2-inch impregnations. Polaroid film was initially used to find workable exposure parameters; subsequent work was done using standard X-ray film. Developing of the X-ray film was accomplished using standard X-ray developer and fixer. Constant motion of the X-ray films was required while they were in the solutions to assure even developing. No more than four X-ray films could be in the individual solutions at one time or damage was incurred by scratching or uneven chemical action. Twenty-four hours were allowed for the drying of the processed X-ray film. All X-ray film processing was accomplished by the author to ensure that desired results were obtained from each impregnation. Appendix B contains the graph used

to determine the length of time X-ray films were left in the developer. Ten minutes was found to be adequate for X-ray films to be left in the fixing solution. Specifications for the materials used in the radiographic processing phase are also listed in Appendix B.

The X-ray negatives were then placed on a light table over tracing paper and oriented in their original positions by using data taken at the beach (e.g., vertical distance from level line and horizontal spacing). The paper was inverted and individual laminations were traced and correlated from one X-ray to the next, forming a vertical cross-section of the beach structure. A second layer of tracing paper was placed over this and inked to produce permanent records. These profiles were then photographed and reduced in size for inclusion in this report.

The sand impregnations were placed vertically in boxes and stored for possible future study. No flowing or deformation of any type has been noted in these impregnations in storage.

B. PHOTOGRAPHIC TECHNIQUES

Beach-cusp migration was noted while collecting data for radiographic analysis, and photography was selected as the best means of studying this phenomenon. In the process of the migration study such factors as beach profile, cusp profile, and rip cell presence were observed.

Reference stakes to be placed in the beach for measuring changes in sand elevation were manufactured. The stakes were

8-ft long with a 3-ft long, 8-inch diameter tube welded on the upper portion (Fig. 27). Four-inch red and white stripes were painted on the tubes for reference. A set of stairs and a large sledge hammer were used to implant the stakes. Eleven stakes were driven 5-ft apart into a "T" formation (six perpendicular to the shoreline and five parallel) centered on the horn of the cusp (Fig. 28 and 29).

In order to cover a tidal cycle photographically during the daylight hours a day was selected when a low tide occurred in the early morning and in the evening with a semi-diurnal high at noon. In this manner the most active cusp movement period was studied with waves overtopping the horn. Commencing at 7:00 a.m. on Jan 28, 1971, a time-lapse movie was made covering the major portion of a tidal cycle. Actual filming was done over a 9-hour period using a super 8-mm movie camera with single framing. A frame was taken after each wave receded to produce the desired results. To ensure stability and uniformly oriented pictures, the camera was mounted on a tripod placed on a concrete anchor used by the sand mine (Fig. 28). At the beginning of the photographic study the bottom edges of all 11 tubes were placed at the sand level. The markers proved to be sturdier than anticipated and withstood several periods of high wave activity prior to their removal in April 1971. Wave energy appeared to be dissipated by the tubes (Fig. 29), and no movement of them was noted during the study.

Aerial views of the area were taken from a helicopter to study the rip cell which was suspected to be associated with the cusp (Fig. 4 through 6). Giant cusps were discovered in these photos which were not evident to the ground observer. Their length from horn to horn was approximately 1000 m (Fig. 5).

III. DATA PRESENTATION

A. RADIOGRAPHIC DATA

After gaining a satisfactory degree of proficiency with the impregnation technique and becoming familiar with the radiographic processing, actual field work was begun on Oct 18, 1970. An undisturbed, representative beach cusp was selected for sampling just north of the Monterey Sand Company Marina Sand Plant (Fig. 8). Subsequent samples were taken on either the first or second cusp to the north of the cable used in the sand operation. The cable provided a permanent reference mark for measuring movement parallel to the coast. A summary of the sampling program is contained in Table I. The remainder of this section discusses the program in chronological order of sample collections.

On Oct 18, 1970, twelve boxes were spaced to ascertain the sand structure in the various parts of the cusp (Fig. 30). The design of this array was arbitrary and conducted solely to determine where subsequent samples should be taken. The results are shown in Fig. 31 and 32. The location of each sample is shown in its proper position and each is numbered on this and all subsequent profiles. The profile made normal to the shoreline revealed cross-lamination and distinct landward-dipping laminae (Fig. 31). The lamination parallel to the shoreline was much more uniform indicating only slight cross-lamination with no dipping or bending of the laminae (Fig. 32). X-rays 4 and

7 indicated the presence of unusual dips or nonconformities in the structure which are considered anomalous (Fig. 31 and 32). The separation between X-rays 1 and 8 was considered too great for inferring any continuity of the lamination structure in the analysis (Fig. 32). The first of these X-ray photographs (or radiographs) and a corresponding photo of each sand impregnation are shown in Fig. 33 through 44. They indicate how the lamination interpretation shown in Fig. 31 and 32 was obtained. Distinct landward-dipping laminae can be seen in X-rays 11 and 12 (Fig. 42 and 44). Interpretation and discussion of these and other features appears in a later section of the thesis.

Since the minor lamination features found in the sequence taken parallel to the shoreline were found in addition to the much more striking structures in those sequences taken normal to the shoreline, it was decided to concentrate on the latter in subsequent data collection. The question then arose as to what time frame was associated with the individual microstructures being observed. Is the life of the laminae associated with tides on a diurnal cycle superimposed on storm and wave action or is it a function of individual wave action during scour and accretion [Eubanks, 1968; Harlett, 1967; Koehr and Rohrbough, 1964]? As a start in ascertaining this cause-effect relationship, the sampling was divided into two, six-box collection sequences. This allowed a comparison to be made between the sedimentary structure of the cusp at low tide and again after a high tide had acted on the cusp.

On the evening of Oct 30, 1970, a sequence of six samples was taken, with the uppermost sample at the horn of the same cusp and the remainder normal to the beach (Fig. 12). This was to be the general pattern for all subsequent sequences.

The analysis of this sequence (Fig. 45) revealed landward-dipping laminae in the bottom of X-ray No. 2 and consisted of minor cross-lamination and lamination similar to those of the previous sequences. Most of the laminae were truncated at the beach surface.

The following morning, Oct 31, 1970, a sequence of six more boxes was taken in exactly the same location and almost exactly the same spacing. This was accomplished by leaving a pipe driven into the horn of the cusp and measuring to the same box locations as the night before. The holes left after the previous day's sampling were filled-in before leaving and individual wave action was observed filling and smoothing the area prior to departure. The second sequence (Fig. 46) shows the wave depositional structure as found in the upper portion of each sample with the homogeneous, unstructured region (Fig. 47 through 50) being the artificially filled sand of the night before. Landward-dipping laminae appeared in this sequence which were not evident in the first sequence (Fig. 46).

On Nov 5 and 6, 1970, two six-box sequences were taken from the horn on the same cusp at the same location and definite structure was evident in the second sequence (Fig.

51 and 52). This was a very active period on the beach with storm activity offshore and the cusp horn moved 10 ft to the north overnight. The difference in beach slopes below the horn (Fig. 51 and 52) was significant and is attributed to the storm activity and varying wave energies superimposed on the tidal cycle.

Two radiographs with photographs of corresponding impregnations (Fig. 53 through 56) from the Nov 6, 1970, sequence were selected for inclusion as they indicate the clarity and definition attainable for microstructure analysis. The landward-dipping laminae in the last sequence (Fig. 52) indicate an even more distinct trend than those of the Oct 18, 1970, sequences. These laminae appear to be more rounded and symmetrical.

A three-box sequence from both the trough and the horn was taken on Nov 9, 1970. Previous trenching had revealed little or no significant structure in the trough area and this sequence (Fig. 57A) substantiated that evidence. Some 30 ft away on the horn there was extreme cross-lamination with landward-dipping laminae (Fig. 57B). Two radiographs with corresponding photographs of the impregnations illustrate the lamination and structural trends (Fig. 58 through 61). Wave action was high overnight and the six-box sequence taken on the same horn location on Nov 10, 1970, 1 ft to the north of the previous sequence with respect to a reference marker placed at sample No. 1 (Fig. 57), indicated that the well-defined landward-dipping laminae

from the previous day had vanished (Fig. 62). A slight hint of still larger landward-dipping laminae was revealed in the right half of the sequence.

During ebb tide with 10-ft breakers and extreme rip activity, a six-box sequence was taken from the horn normal to the surf zone on Nov 16, 1970. The cross-lamination structure appeared periodic and a indication of the landward-dipping laminae appeared between X-rays 3 and 5 (Fig. 63). One X-ray from this sequence was photographed along with the corresponding impregnation to illustrate the laminae detail and cross-lamination (Fig. 64 and 65). The following morning two, three-box sequences were taken, one in the trough, normal to the surf zone where surface ripple marks were evident to the unaided eye, and a second sequence about 35 ft seaward from the horn sequence taken the day before. It was anticipated that the observed ripple marks of the first sequence would be indicative of subsurface ripple structure as well, but none was found (Fig. 66B). The second sequence (Fig. 66A) produced one of the most interesting X-rays taken during the entire investigation revealing well defined cross-lamination in the lower portion (Fig. 67 and 68). The cross-lamination may have resulted from changing wave and tidal influences causing radical erosion and deposition features.

By Nov 20, 1970, the winter profile of the beach was fully developed and a pipe was placed at the horn of the first cusp to the north of the sand dredge cable. A six-box

sequence was taken that evening and the sand level on the reference marker was noted. The radiographic analysis (Fig. 69) revealed nothing extraordinary and the only indication of slight landward-dipping laminae was in the lower left series of X-rays. The days preceeding this sequence were typified by small, 3-ft breakers and moderate weather. The parallel structure is attributed to these conditions. However, the lack of wave action and extreme tides had no effect on the dynamics of the cusp as the horn migrated 94 inches northward overnight and the level of sand on the reference marker was lowered 10 inches. A six-box sequence, taken Nov 21, 1970, is shown in Fig. 70. Close scrutiny of the X-rays revealed the landward-dipping laminae again in the lower left X-rays. The fineness of the structure and uniformity of deposition as compared to a previous sequence taken during a period of more wave activity is notable (compare Fig. 57 and 70).

A final sequence was taken Jan 23, 1971. The step-by-step procedure for data collection described in earlier sections was illustrated by photographs taken during this sampling sequence (Fig. 12 through 26). Radiographic analysis of this sequence (Fig. 71) indicates the recurrence of the landward-dipping laminae. A dip was evident in X-ray 8 and is discussed in a later section. To further illustrate the detail and definition attainable with radiographic analysis of impregnations, the photographs of the six impregnations and their respective radiographs have been

included in Appendix C. Comparison of the radiographs to the macro-features found in trenching (Fig. 14 through 17) indicates the former's obvious value in microstructure investigations.

B. PHOTOGRAPHIC DATA

Nine marker stakes were placed with the bottoms of the tubes at the sand surface on Jan 26, 1971, after impregnation studies were terminated. The following evening significant erosion and horn migration was noted (Fig. 72) prior to implanting the remaining two markers. On Jan 28, 1971, a time-lapse movie was made of the marker stakes during a 9-hour period covering profile changes occurring during a complete tidal cycle. At 7:00 a.m. (PST) when the photographing was commenced, the bottoms of all eleven marker tubes were level with the beach surface (Fig. 73). As the tide began to flood, the lower markers indicated erosion was taking place with a migrating mound of sand at the advancing shoreline (Fig. 74). By 10:00 a.m. the erosion process had lowered the profile approximately 18 inches on the lower marker (Fig. 75). Erosion appeared complete at high tide and a semi-stable equilibrium profile was assumed at 11:12 a.m. (Fig. 76). Ebb tide did not produce any appreciable deposition of sand and the profile established during flood tide was essentially unchanged after ebbing was completed at 4:00 p.m. (Fig. 77). A copy of the motion picture on Super 8 mm film made during this study is on file at the Naval Postgraduate School, Department of Oceanography

(Code 58Ad), and is available to interested investigators on a loan basis.

The marker stakes were left in place and used to study the general movement of the beach cusp during the period from Jan 28, 1971, to April 1, 1971. Observations of horn location relative to the original stakes were taken during the period and these are shown in Fig. 78. Spring tides occurred on the following dates: Jan 28, Feb 23, and Mar 28. Neap tides occurred on the following dates: Feb 14 and Mar 15.

Scarping of the cusp was seen to occur after a period of extremely calm weather (Fig. 79). Cusp degradation was coupled with this, but the cusp never disappeared.

IV. DATA ANALYSIS AND CONCLUSIONS

A. SAND STRUCTURE ANALYSIS AND CONCLUSIONS

Readily evident in the radiographs are laminae which are otherwise invisible in visual inspection of the impregnations (e.g., compare Fig. 58 and 59, 64 and 65, 67 and 68). Without the use of radiographs only statements concerning gross macro-structure could be made concerning thick (1- to 10-cm) banding.

In a comparison of radiographs and photographs it was found that when the resin penetration in a given impregnation was approximately the same in adjacent layers, the thin (1 to 3 mm in thickness), light-banded layers in the radiographs corresponded to layers containing higher concentrations of dark-colored heavy minerals such as magnetite and hornblende. The thin, dark bands were dominated by light-colored minerals such as quartz and feldspar. This reversal of color patterns held true except in cases of large differences in penetration of resin between layers resulting in exaggerated ridging of the impregnations. The color patterns then became mainly a function of thickness.

Ridging was noted in all impregnations to varying degrees ranging from barely discernable ridges to ridges 3 inches high (Fig. 23). If insufficient hardener was added, the resin penetrated much farther into certain laminae. When irradiated these higher ridges appeared as light banding and

could be erroneously analysed as laminae of heavy minerals (Fig. 67 and 68). The unusually high ridges appeared to be of coarser material than the bordering laminae, indicating that the depth of impregnation is a function of sand porosity and permeability. The amount of reworking by swash action apparently determines packing and firmness which might also help explain the ridging [Scott, 1954]. On impregnations with a more uniform depth of penetration the radiographs revealed microlaminae within the less exaggerated ridges (Fig. 58 and 59).

The general laminae structure observed in the radiographs is believed to represent a dual lamination in the upper swash zone [Clifton, 1968]. Dual lamination, consisting of a fine, heavy mineral dominated zone at the bottom of a given laminae grading to a coarse lighter mineral region at the top, was encountered in all samples taken during this study. Dual lamination is believed to be evidenced in the radiographs by the alternate light and dark banding of individual laminae (Fig. 64 and 65).

Inman and Filloux [1960] proposed that the vertical thickness of the laminae is indicative of the degree and intensity of erosion and deposition. The radiographs correlated with the visual wave data taken at the time of sample collection supported this hypothesis. Thicker laminae were found whenever moderate to high wave activity existed or had existed during the tidal cycle before sampling (Fig. 57). Conversely, thin laminae were evident during calm periods

(Fig. 70). The variations in the thickness of individual laminae may be explained by a variation in incoming individual wave energies resulting in differing depths of swash erosion or accretion [King, 1951]. Other factors to which the laminae thickness is related are the slope of the beach, speed of swash, angle of wave attack on the beach cusps, grain size, and cut or fill of the profile during a tidal period [Otvos, 1965].

No rhythmic lamination that might be associated with tidal variations was discernable during this study. This is in agreement with Thompson [1937]. Perhaps the best illustration of a lack of pattern was the Oct 31, 1970, sampling sequence (Fig. 46) in which impregnations from the same location were taken one tidal cycle after the first ones were procured (Fig. 45). Individual wave action was observed by the author to be responsible for lamination.

Utilizing the radiographic analysis profiles as guides, general conclusions were drawn concerning the beach structure perpendicular to the shoreline compared to that parallel. Study of the cusp microstructure revealed regular laminae of light-colored sand alternating with dark sand laminae in vertical cross sections parallel to the shoreline. Typical of the impregnations taken parallel to the shore line were wide, thin laminae of sand deposited by the backwash. These result from fan-shaped regions of deposition left by individual swashes as the tide recedes (Fig. 80). Trenching of the cusp in the direction parallel to the shoreline indicated

that the laminae ranged from 1 to 10 m in length with a slope following the sand surface from the horn to the trough of the cusp. Less pronounced surface laminae truncation was found in this direction than in impregnations taken perpendicular to the shoreline. The amount of subsurface cross-lamination was also much less in the direction parallel to the shoreline than in the perpendicular direction. Sampling was ceased along profiles parallel to the shoreline after observing little or no noteworthy structural features in this direction.

In contrast to the general evenness and regularity found in the parallel sampling profiles, the impregnations made perpendicular to the shoreline revealed uneven laminae thickness, laminae whose length varied from a few centimeters to several meters, distinct cross-lamination, anomalous dips and unstructured regions, and landward-dipping laminae.

The varying laminae lengths observed were attributed to the uprush-backrush extent of each swash-backwash cycle. The degree to which each swash extends shoreward varies significantly during a tidal cycle. In addition truncation due to the frequently changing profile also results in short laminae lengths. The longer laminae lengths found in samples parallel to the shoreline are a function of the general uniformity of the swash uprush laterally along the beach (Fig. 80). In the profiles there appeared to be a gradation from short to long laminae as one proceeded from the horn to the inner trough of a cusp (Fig. 81). This may

be explained by the flow patterns of water over a cusp (Fig. 9). The horn is under direct attack with a concentration of energy while the trough area is more a region of generally low energy due to local wave refraction and low angle of attack by waves. The laminae from individual swash and backwash deposition are considered to be the basic components of the microstructure found throughout this investigation (Fig. 80 and 81).

The four distinct types of cross-lamination noted by Thompson [1937] were readily apparent in profiles drawn during study of the radiographs (Fig. 10). Examples of each are: (1) Types A and D, Fig. 66, X-ray No. 11; (2) Type B, Fig. 52, X-rays 9 and 10; and (3) Type C, Fig. 31. No other types were observed and Type D was least common. Radiographic analysis of the impregnations made during this study revealed that the lamination is much thinner than those originally described by Thompson [1937]. He described the laminations as being from a few inches to 10 ft in thickness and from a few feet to 200 ft in length. Angles between the laminations at the angular unconformities range from about 8° (Fig. 65) to about 15° (Fig. 68). Cross-lamination was evident to some extent in all sample sequences perpendicular to the shoreline and nearly nonexistent in those parallel to the shoreline. This was attributed to the wave runup flow pattern (Fig. 9) which indicates a generally even flow of swash from the horns into the troughs resulting in a regular laminae structure with little or no cross-lamination in the

trough [Russell and McIntire, 1965]. Conversely, on the horns there is a constant flow directly onto and then away from the area into the trough resulting in active cutting and deposition producing distinct cross-lamination. Duncan [1964] has proposed that cross-lamination may result from deposition by flood-tide swashes succeeded by ebb-tide swashes. It must also include the cutting away of old laminae during high tide buildup and changes in the wave regime. This probably explains the cross-lamination in Fig. 55, 56, 67 and 68. Other factors which may cause cross-lamination are spring and neap tides, currents, local flow patterns, texture of the sediment, and slope over which the sediment is moved.

The anomalous dips noted in some radiographs were attributed to several factors. Shallow, symmetrical dips in an individual impregnation were a result of slumping and packing during transit of the sample from the beach to the impregnation area. These contributed in no way to loss of clarity or difficulty in interpretation of features as all features were deformed equally. Short, steep, symmetric dips were interpreted to be foot prints which had been filled by wave action and eventually smoothed to conform with the beach profile (Fig. 31 and 71). Wide, moderately steep and unstructured areas obviously not continuous with the remainder of the profile were believed to be beach-buggy tire tracks (Fig. 32).

The most unexpected result of the study was the appearance of subsurface landward-dipping laminae in the vicinity

of the horn. This feature appears in all perpendicular profile sampling sequences except one, and it was felt that had the boxes been longer, or had a staircase sampling technique been employed, landward-dipping laminae would have been found at greater depths and at other locations across the beach profile. The probable explanation for these laminae relates to the profile of the horn surface. The cusp horns studied on Monterey Bay were observed to have a slight rise at their apex with a landward dip toward the berm. As waves crested over the horn at high tide, sand deposition built the horn up so that an indentation formed on the landward side on the berm resulting in a more peaked structure. At times of high tide and during the initial ebb of the tide, sand was deposited on the horn leaving the peak buried. The buried horn is believed represented by the crest of the landward-dipping laminae. The steepness and curvature of the laminae at the cusp apex may be due to the extent of wave and tidal action at the time of formation during burial.

B. PHOTOGRAPHIC ANALYSIS AND CONCLUSIONS

The time-lapse movie provided striking evidence of two closely related phenomena taking place on the beach cusp; general beach cusp profile changes during a tidal cycle resulting in erosion and deposition on the beach surface, and individual wave action producing random fan-shaped swash patterns on the beach surface (Fig. 80 and 81). The erosion and deposition phases are felt to be the major contributing factors of cross-lamination noted in the radiographs.

Superposition of local wave action on the receding tide apparently results in the rhythmic stratigraphic structure. A distinct, migrating mound of sand was observed to move ahead of the advancing tide as may be seen in a comparison of Fig. 72 through 76. At high tide this feature disappeared and a general eroded surface profile was assumed until deposition commenced as the tide receded.

The individual waves which deposited and scoured the sand resulted in the laminae revealed in the radiographic analyses. Individual waves were totally random in their depositional fan-shaped areas near the cusp horn, but the deposition in the trough resulted in more regular laminae spread over a larger area (Fig. 80 and 81). This may explain the absence of significant cross-lamination and the presence of long laminae of sand observed in the trough as compared to the horn, where cross-lamination and short laminae were evident.

The migratory movements of the cusp observed during the study indicate a direct relation between spring and neap tidal cycles and cusp position (Fig. 78). Upon the approach of spring tides, the cusp position migrated shoreward. Seaward migration occurred in the period before neap tides. This is in agreement with the previous work of Shepard [1935] who found that there is a definite relationship between cusp location and tidal cycles. It must be noted that high wave activity superimposed on either of these cycles may produce different results.

Prior to the placement of the marker stakes in the beach it was believed that the cusps might be part of a progressive wave pattern as originally hypothesized by Escher [1937], and that there was extensive movement of the cusps up and down the coast with changes in the wave characteristics. During the period of observation with the reference stakes no such along-shore movement was observed (Fig. 78). The horn appeared to migrate within a limited area and was seen to deteriorate slightly with the onset of calmer wave conditions. On one occasion some scarping was observed along the entire cusp (Fig. 79). There were no major storms during the observation period and the giant cusps in the area also remained in the same location.

It is proposed that the beach cusp under study is one of the hierarchically arranged cusps of Dolan and Ferm [1968] between two larger giant cusp horns, and is somehow related to the larger cusp horn locations. The minor movement of the beach cusp horn (Fig. 78) is attributed to variations in wave action and the tides. It is felt that, had the giant cusp horns with their corresponding rip cells been migrating, the ordinary beach cusps also would have moved in relation to them up or down the coast.

V. SUMMARY

The use of radiographic analysis in studying the micro-structure of beach cusps revealed varying types and amounts of cross-lamination, varying lengths of sand laminae, varying lamination thicknesses, and what appear to be relic horns of old cusps. The degree of cross-lamination observed was found to depend upon whether the profile was taken perpendicular or parallel to the shoreline. Profiles taken perpendicular to the cusp horn revealed the most well-defined cross-lamination, with a gradual reduction in cross-lamination to the area of the trough where minimum structure was found. This reduction is attributed to the reduced wave energy and the uniformity of the swash reaching the inner trough region. Conversely, the horn is subjected to greater wave attack from continually varying angles resulting in extreme cross-lamination. Profiles made parallel to the upper surf zone revealed almost no cross-lamination except near the horn. The lack of structure in this direction is considered indicative of the current flow pattern in this region (Fig. 9).

The lamination lengths observed were shortest at the horn and in the profiles perpendicular to the shoreline. Swash deposition producing these laminations was observed to spread out in fan-shaped areas on the beach face with the axis of the fan perpendicular to the waterline (Fig. 81). These fans

were much wider in the parallel direction and overlapped by many feet during succeeding swashes (Fig. 80).

The lamination thickness appears to be dependent on the wave energy. During periods of small waves the laminae were thin and uniform. High wave activity produced much thicker and more variable laminae structure.

The sub-surface landward-dipping laminae observed in the radiographic analysis are interpreted as relic horns of old cusps. These horns are believed to be modified and buried during changes in wave and/or tidal action.

The presence of a giant cusp and the existence of a littoral cell in the area of study were revealed from the aerial photography. From horn migration observations it is postulated that the cusp studied in this investigation is one of a group of beach cusps located between two giant cusp horns. The beach cusp in this study maintained a relatively fixed location between the two larger cusp horns and only minor migration occurred as a result of local wave and tidal regimes. It is postulated that should the larger cusp horns migrate, the beach cusp studied in this thesis would move along the coast relative to this migration.

VI. RECOMMENDED FUTURE STUDY

In future field work on cusps, deeper, more extensive and more closely spaced sampling, lower down on the beach and in the troughs as well as on the horns, should provide a more meaningful insight into cusp structure and subsurface lamination. A staircase sampling technique with the Senckenberg box would allow a deeper cross-section to further delineate the landward-dipping features observed.

The principal shortcoming of this investigation was the almost total lack of adequate wave data. It is recommended that future investigations include placement of a wave recorder to the seaward of the area of study. With a wave recorder a much more definitive description of cusp life vs. wave and tide regimes may be made. The study of laminae structure would also be aided if wave data were available.

Textural and mineralogical analyses of the individual layers found in the impregnations would be useful. This could be accomplished using thin sections cut from the impregnations or using sand grains from the impregnations. A study of permeability of individual layers should also prove useful.

Permanent reference markers should be placed at the start of future investigations. These would serve a two-fold purpose; (1) to provide a reference for migration studies, and (2) if placed on the beach cusp surface they would be available for cusp profile and lamination studies.

Profile measurements should be made to determine topographic changes in the cusp over short intervals of time, i.e., a semi-diurnal tidal cycle or oftener, fortnightly tidal cycle, and through a storm sequence.

Although this investigation concerned itself with a problem in recent marine sedimentology, it is felt that further work may contribute to identification or recognition of ancient beach deposits. Recognition of relic beach cusps or lamination features in the geologic column would provide information as to the environment existing at the time. The investigative process of using the radiographic analysis technique in conjunction with impregnations provide the sedimentologist with a powerful tool.

TABLE I

FIELD SAMPLING PROGRAM

| DATE | SEQUENCE NO. | DESCRIPTION |
|--------------|--------------|--|
| Oct 18, 1970 | 1 | 5 boxes down slope from horn normal to surf zone (X-rays 6,9,10,11,12) 1 box in trough normal to surf zone (X-ray 7) |
| Oct 18, 1970 | 2 | 5 boxes across horn parallel to surf zone (X-rays 1,2,3,4,5) 1 box in trough parallel to surf zone (X-ray 8) |
| Oct 30, 1970 | 3 | 6 boxes down slope from horn normal to surf zone (X-rays 1,2,3,4,5,6) |
| Oct 31, 1970 | 4 | 6 boxes down slope from horn normal to surf zone (X-rays 7,8,9,10,11,12) |
| Nov 5, 1970 | 5 | 6 boxes down slope from horn normal to surf zone (X-rays 1,2,3,4,5,6) |
| Nov 6, 1970 | 6 | 6 boxes down slope from horn normal to surf zone (X-rays 7,8,9,10,11,12) |
| Nov 9, 1970 | 7 | 3 boxes down slope from horn normal to surf zone (X-rays 1,2,3) 3 boxes in trough normal to surf zone (X-rays 4,5,6) (high wave activity) |

TABLE I (continued)

| | | |
|--------------|----|---|
| Nov 10, 1970 | 8 | 6 boxes down slope from horn normal to surf zone (X-rays 7,8,9,10,11,12) |
| Nov 16, 1970 | 9 | 6 boxes down slope from horn normal to surf zone (X-rays 1,2,3,4,5,6) |
| Nov 17, 1970 | 10 | 3 boxes down slope from horn normal to surf zone (X-rays 10,11,12) 3 boxes in trough normal to surf zone (X-rays 7,8,9) |
| Nov 20, 1970 | 11 | 6 boxes down slope from horn normal to surf zone (X-rays 1,2,3,4,5,6) |
| Nov 21, 1970 | 12 | 6 boxes down slope from horn normal to surf zone (X-rays 7,8,9,10,11,12) (low wave activity) |
| Jan 23, 1971 | 13 | 6 boxes down slope from horn normal to surf zone (X-rays 7,8,9,10,11,12) |

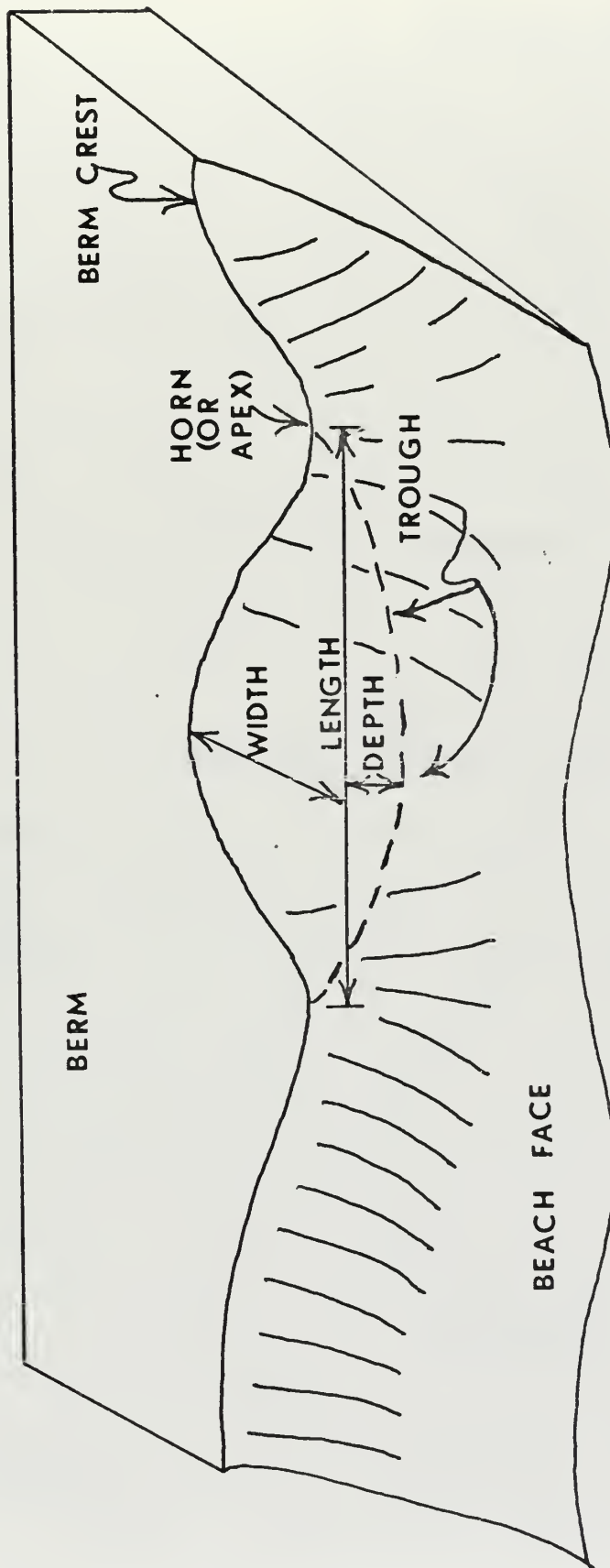


Figure 1. Beach cusp terminology.

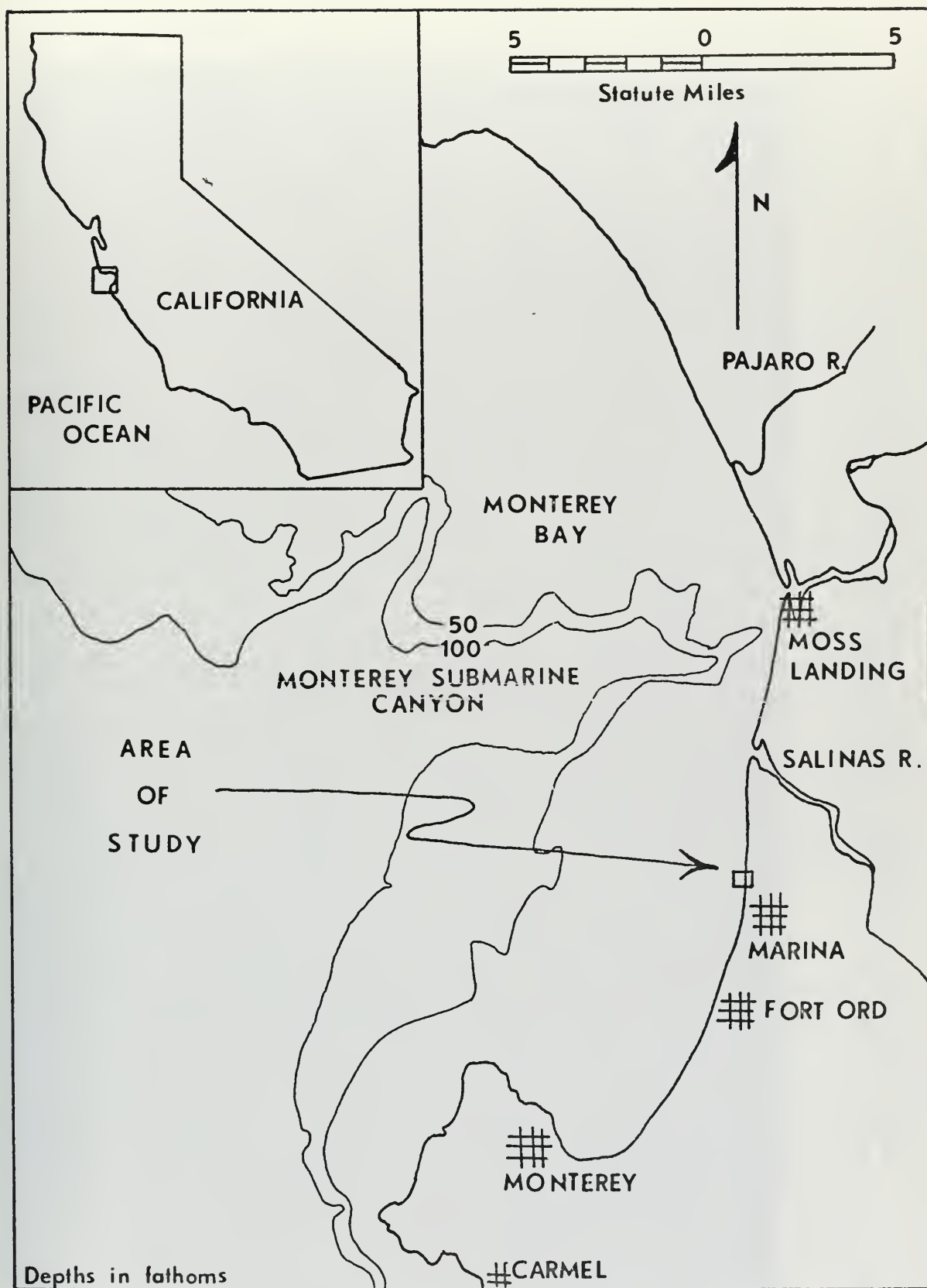


Figure 2. Monterey Bay and area of study.

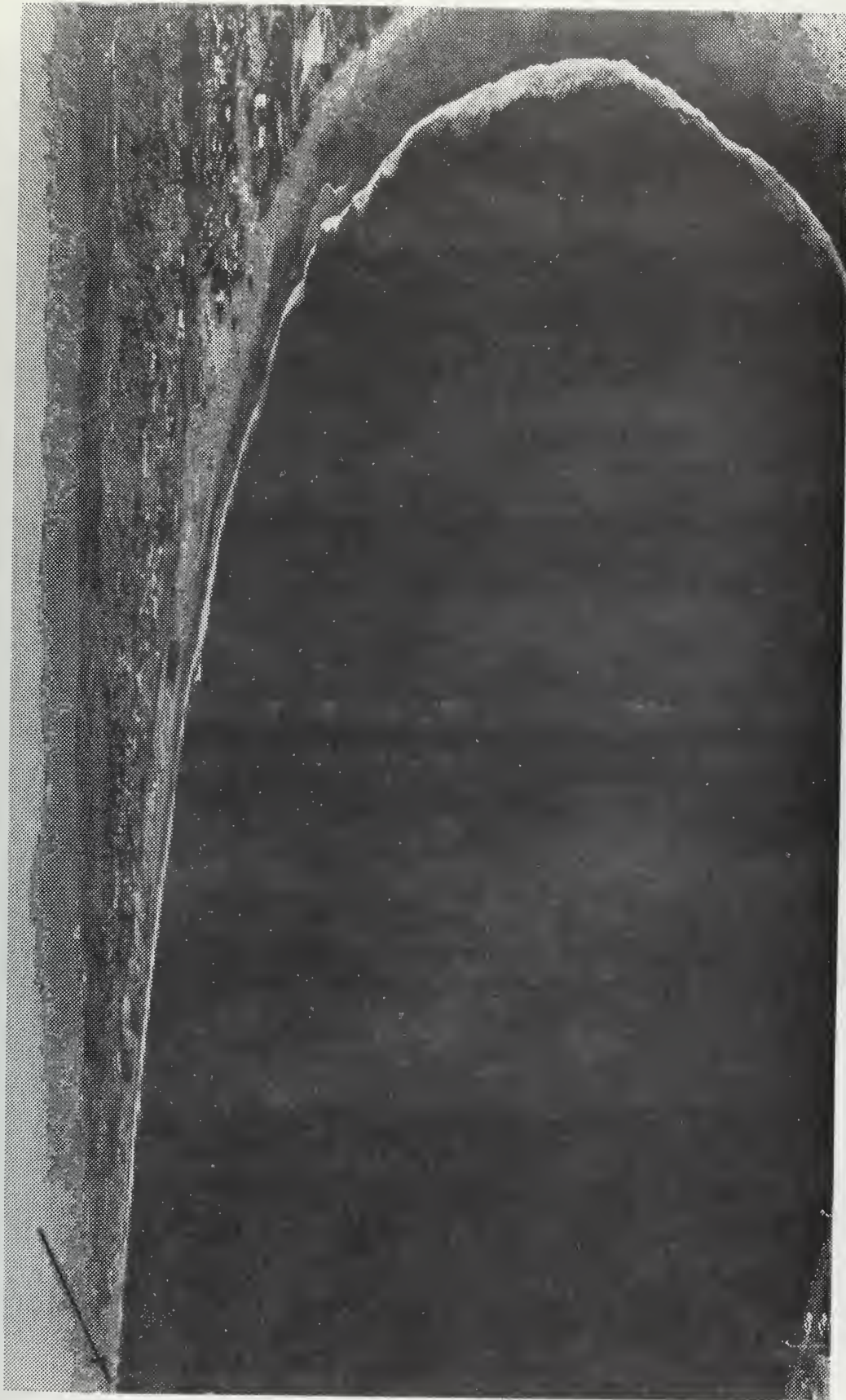


Figure 3. Aerial view of southern half of Monterey Bay. Photo taken looking north-east from above Monterey Harbor. (Arrow points to area of study.)

AREA OF STUDY

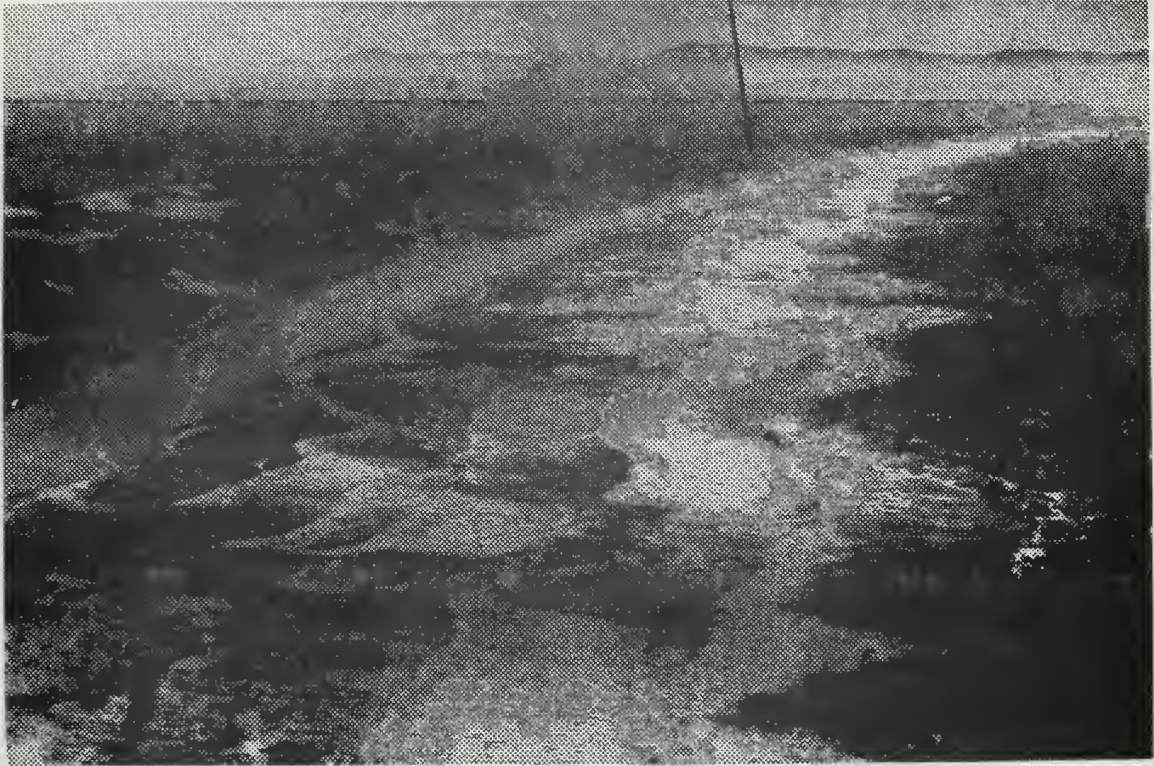


Figure 4. Aerial view of mid-southern Monterey Bay. Photo taken looking south from mouth of Salinas River.



Figure 5. Aerial view of Marina Beach. (Note the giant cusps with smaller beach cusps on upper beach grouped between their horns. Arrow points to area of study.)



Figure 6. Aerial view of Marina Beach and Quaternary dune field.



Figure 7. Beach cusps to south of sand mine on Marina Beach.



Figure 8. First beach cusp to north of sand mine.



Figure 11. Senckenberg sample box.

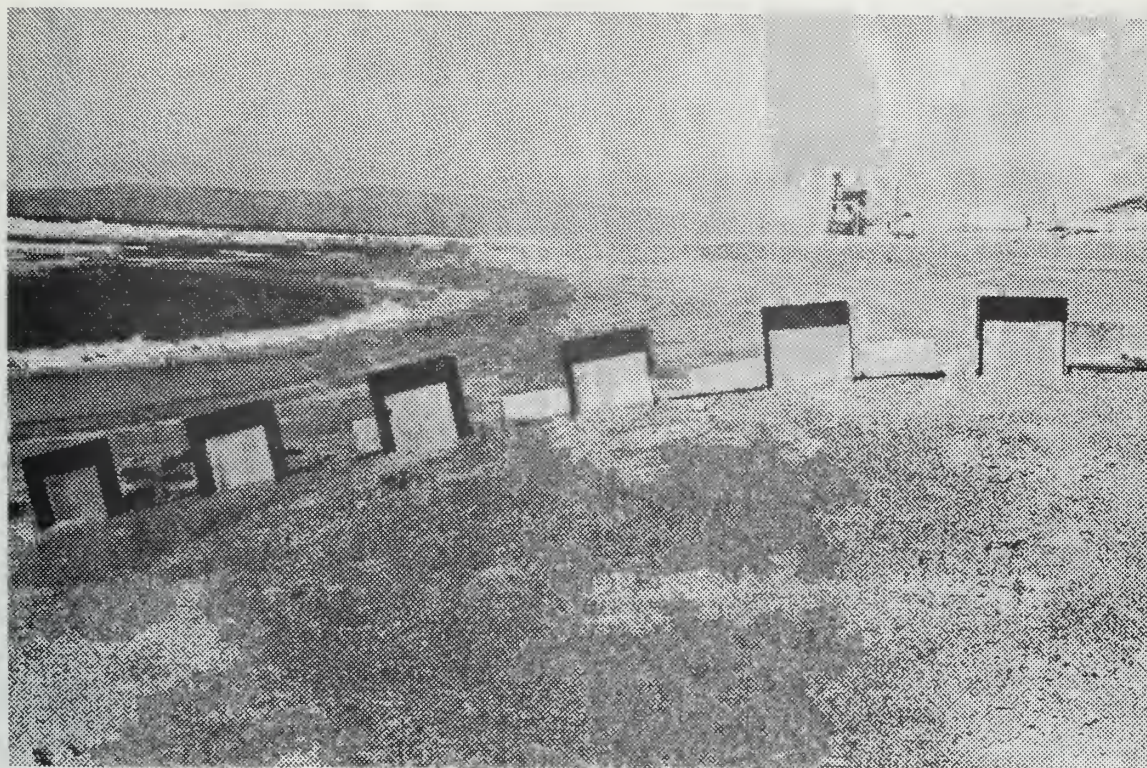


Figure 12. Sample boxes positioned for pressing into cusp.

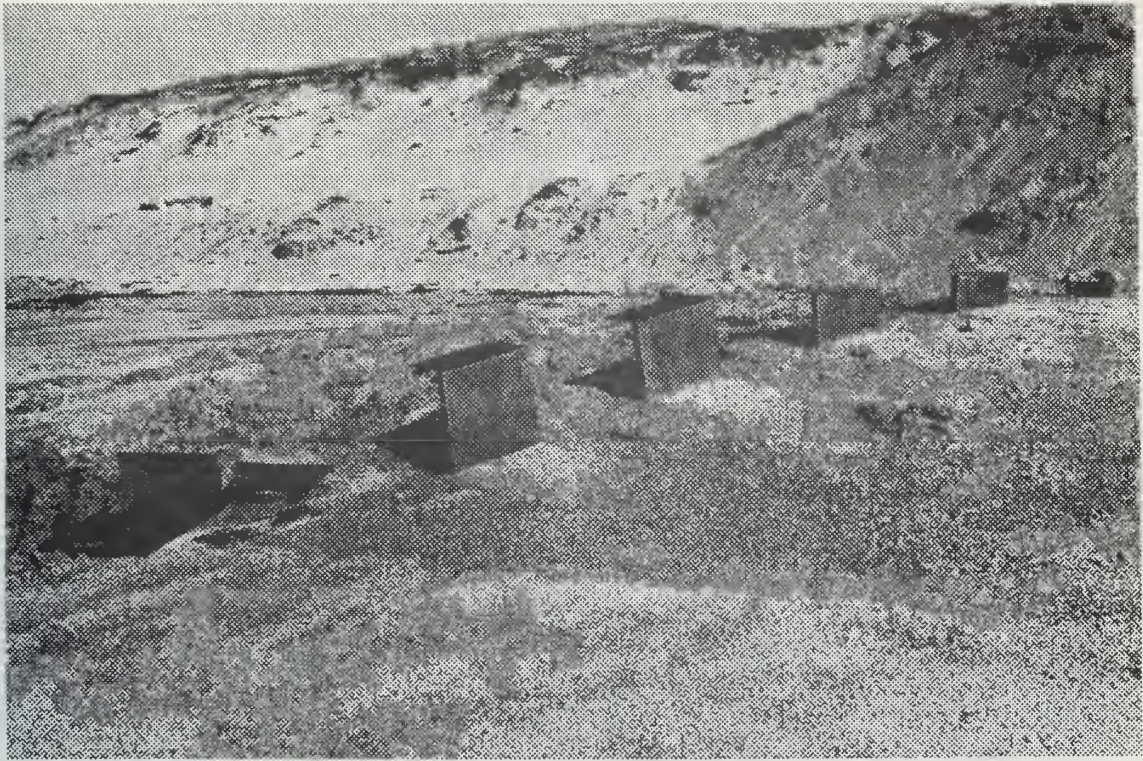


Figure 13. Sample boxes in position with sides in varying stages of placement.

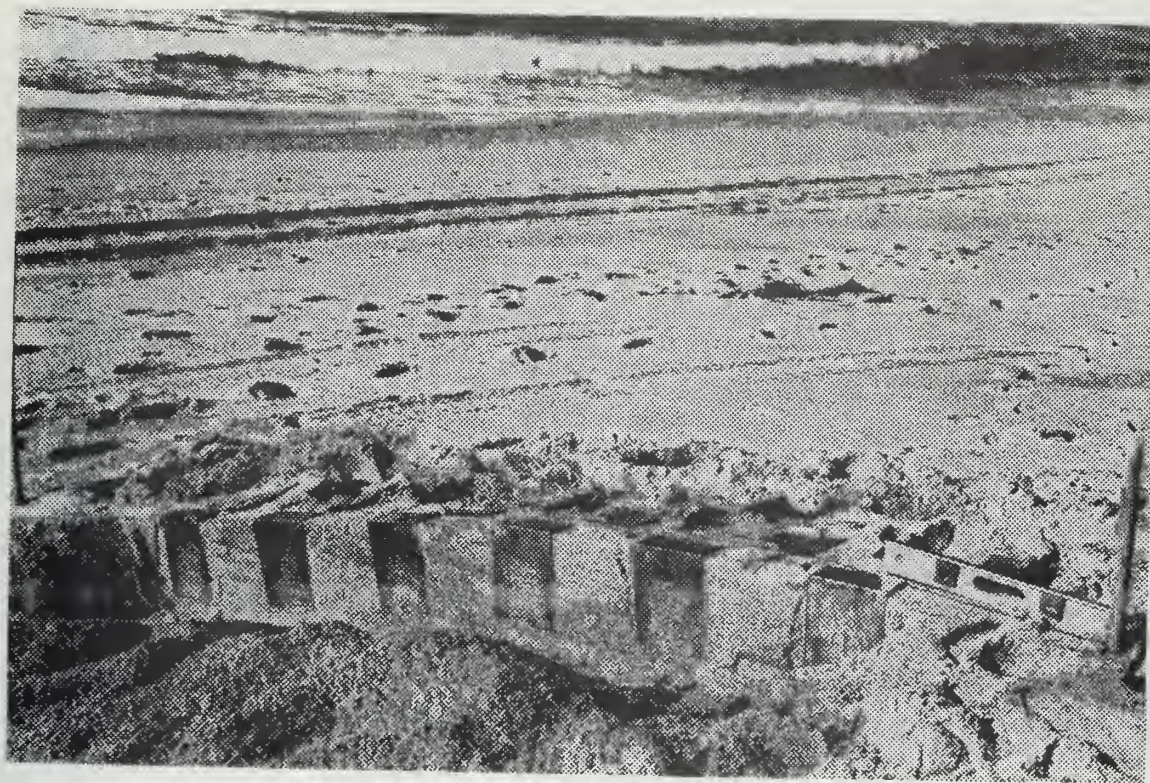


Figure 14. Sample boxes with sides in position, sand removed, and level line in place.

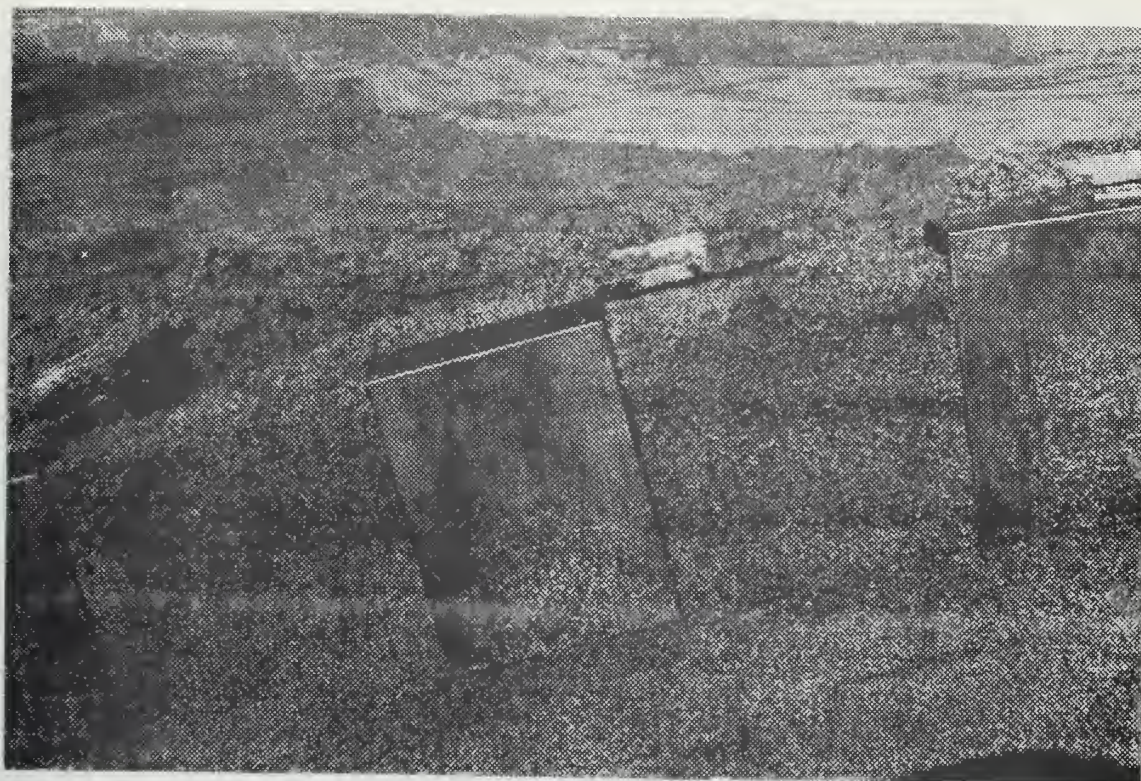


Figure 15. Close-up of macro-lamination.

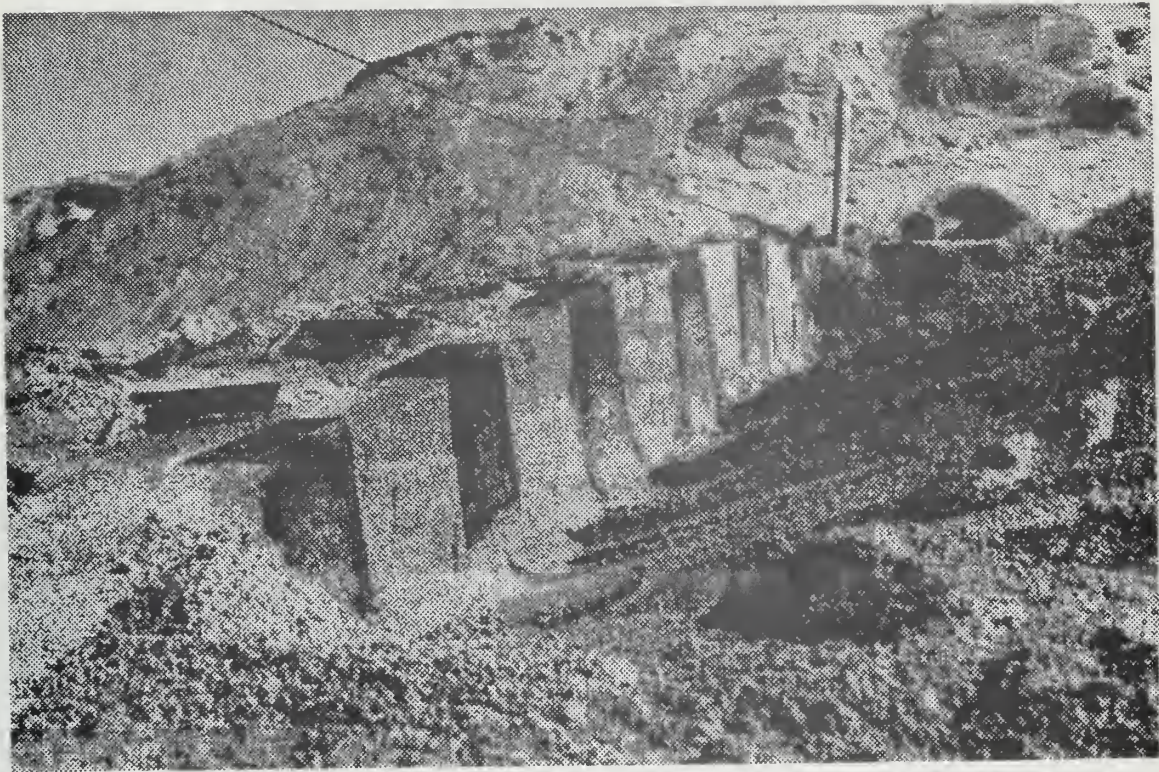


Figure 16. Overall view of macro-lamination and relationship to box samples.

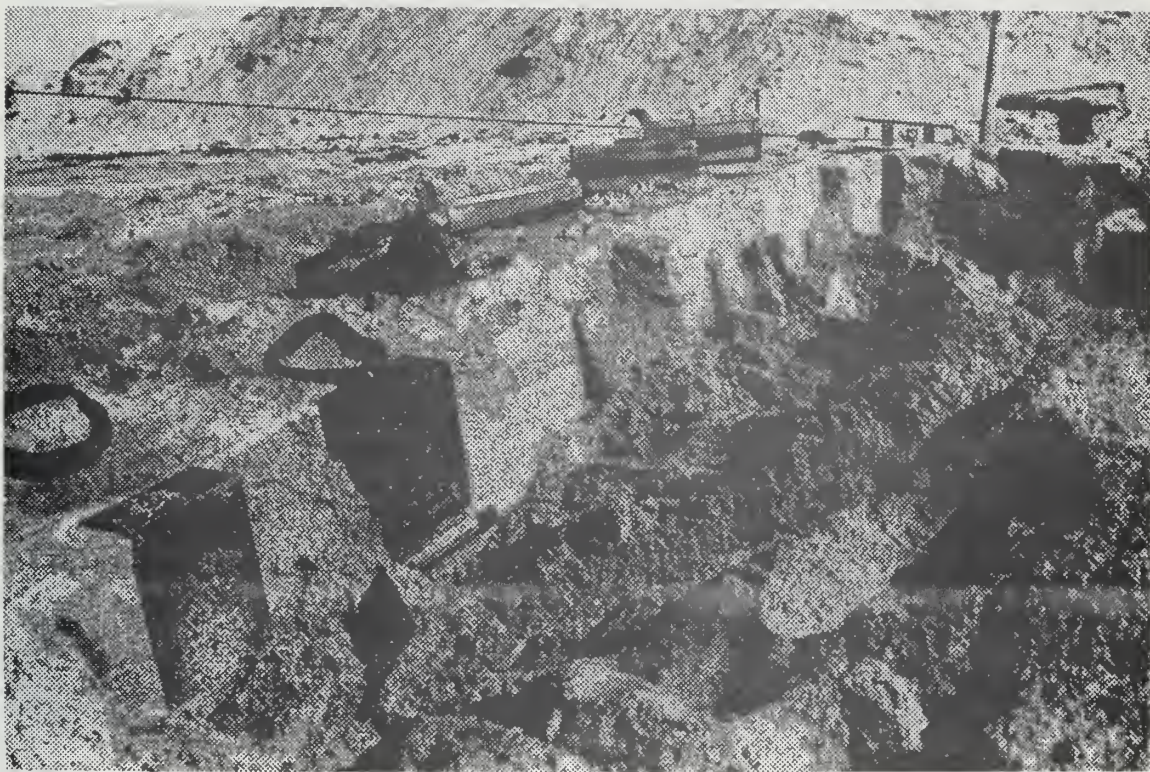


Figure 17. Sample boxes being removed from sand.



Figure 18. Sample boxes at Beach Laboratory.



Figure 19. Pouring resin with hardener over sand sample.



Figure 20. Sample boxes with rubber bands and bottom plates removed. (Note the depth of resin penetration.)



Figure 21. Sample boxes with loose sand and impregnations being removed.



Figure 22. Impregnations as they came from sample boxes before tapping off loose sand.

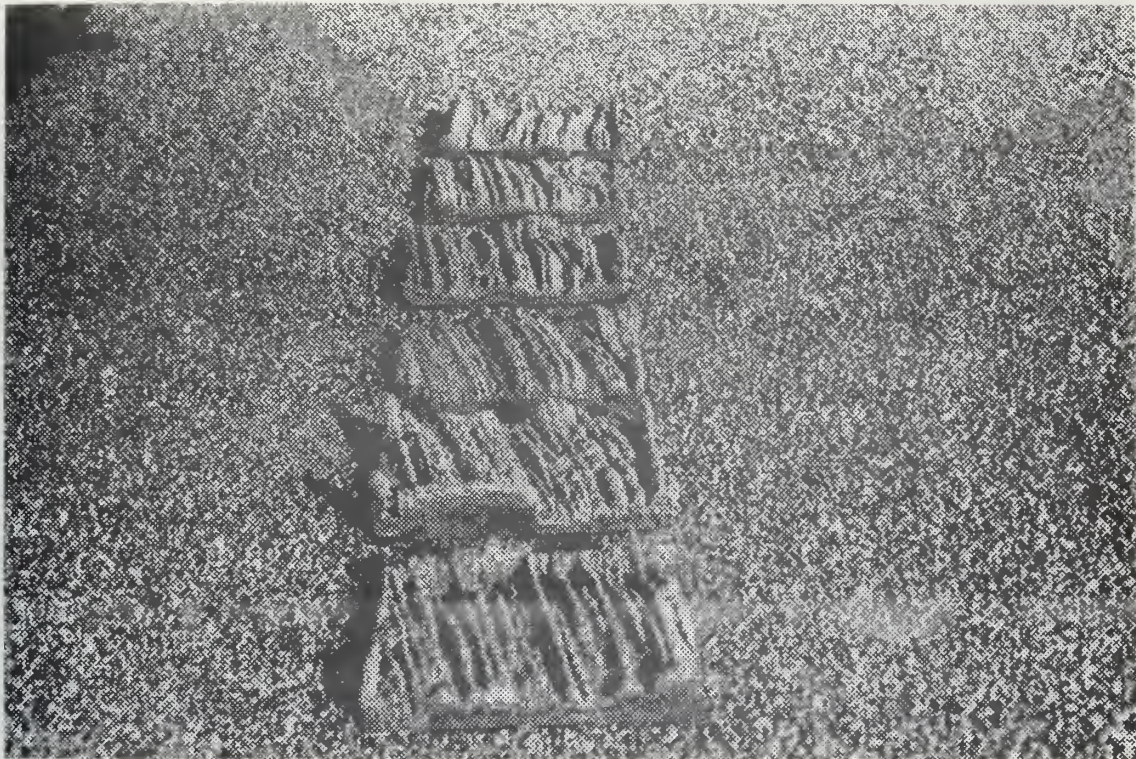


Figure 23. Six impregnations taken on Jan 23, 1971, with loose sand tapped off revealing distinct ridges and degree of impregnation.

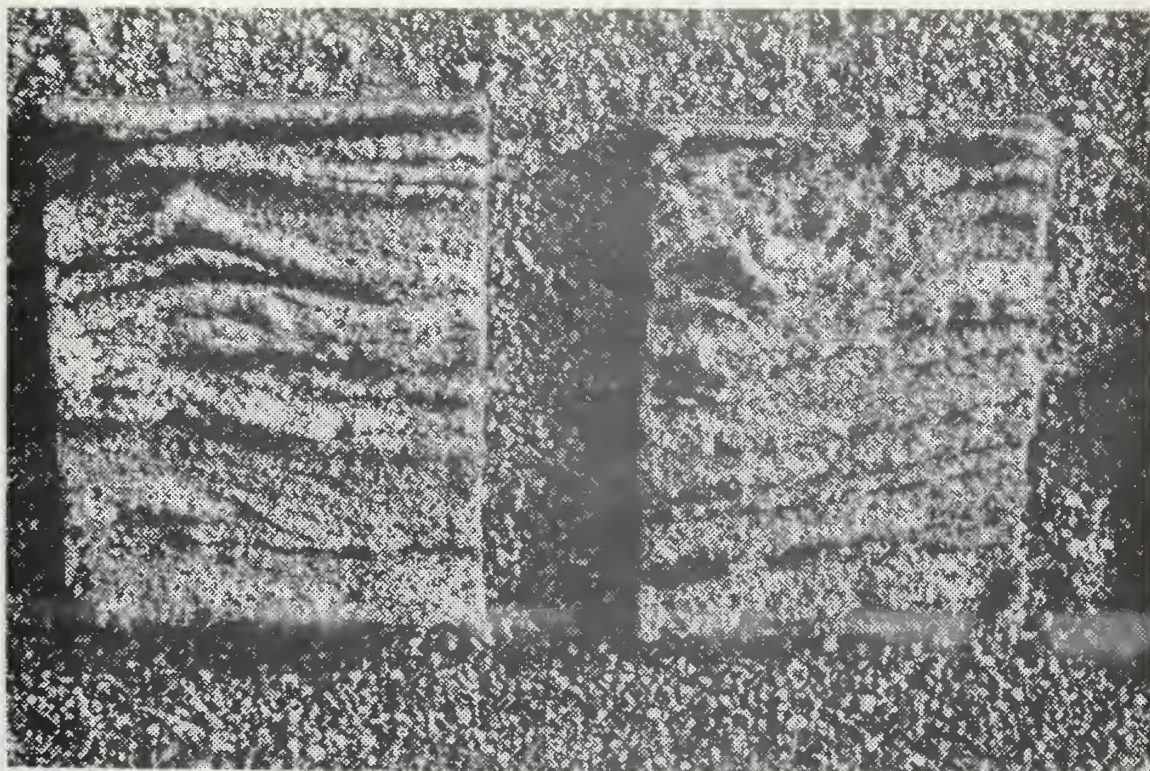


Figure 24. Close-up of ridging and structure found in impregnations.



Figure 25. Each impregnation labelled by number, date and orientation to beach surface (with lead letters on masking tape).

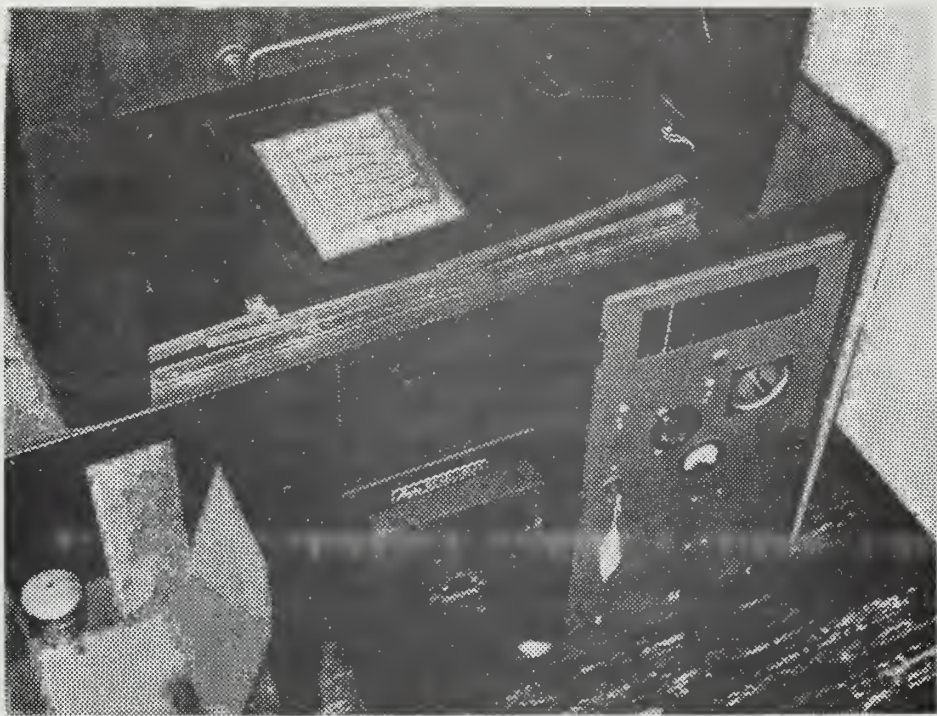


Figure 26. Impregnation in X-ray machine.

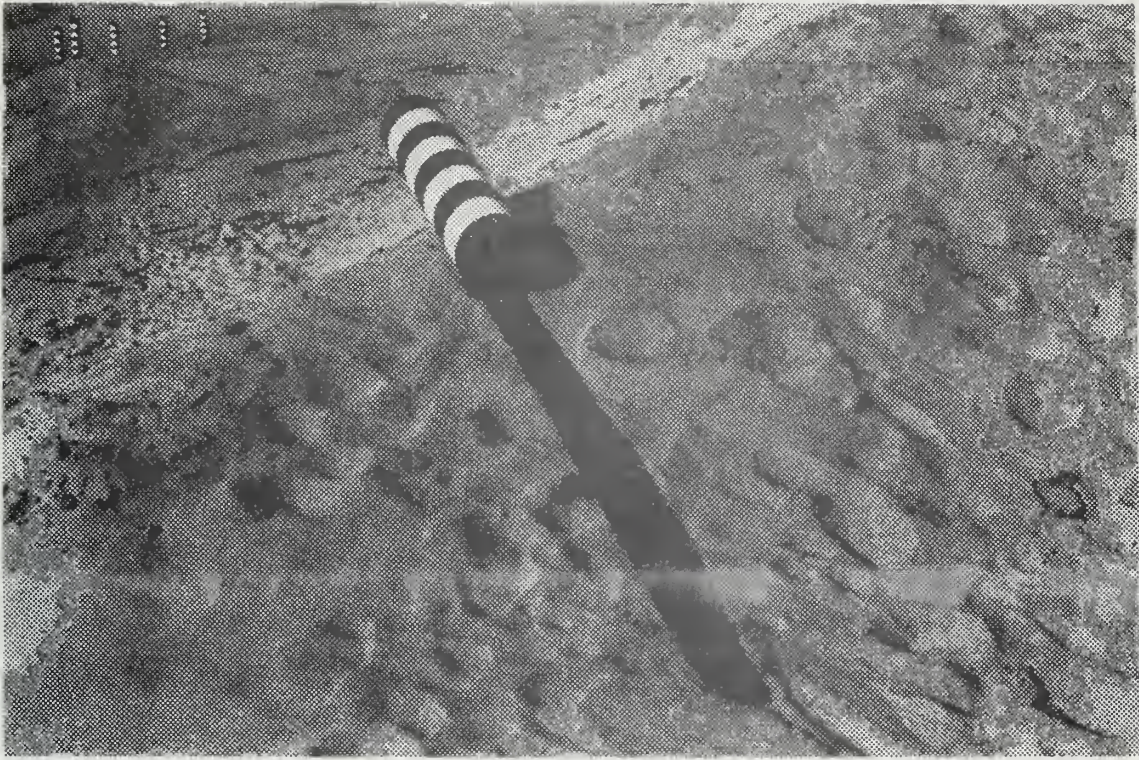


Figure 27. Marker stake.



Figure 28. Time-lapse movie location and equipment.



Figure 29. Surf breaking on marker stakes.

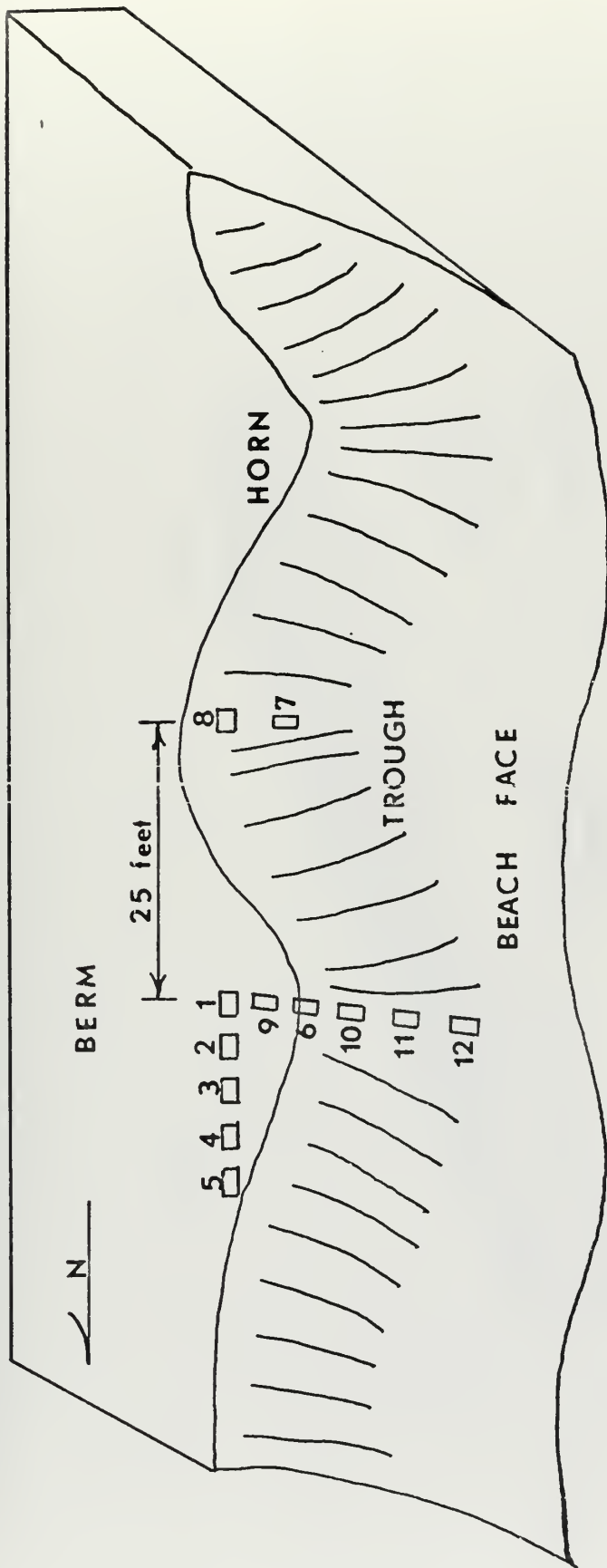


Figure 30. Sampling box locations for Sequence No. 1 taken on Oct 18, 1970.

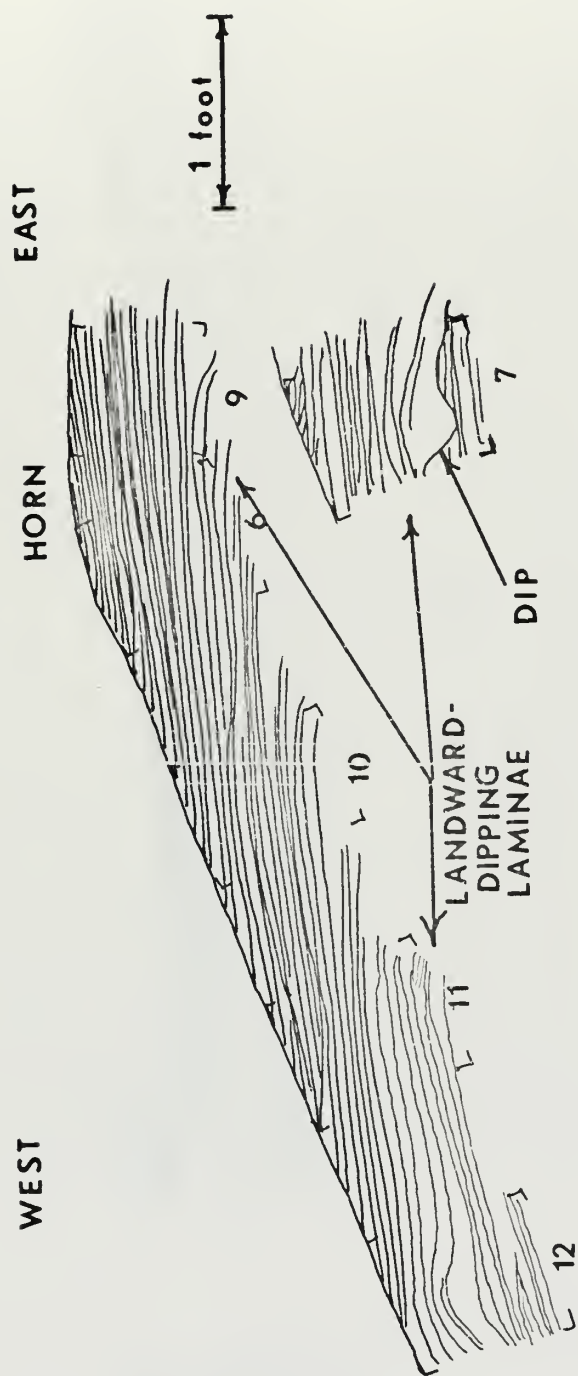


Figure 31. Radiographic analysis of 6 X-rays from Oct 18, 1970, Sequence No. 1.

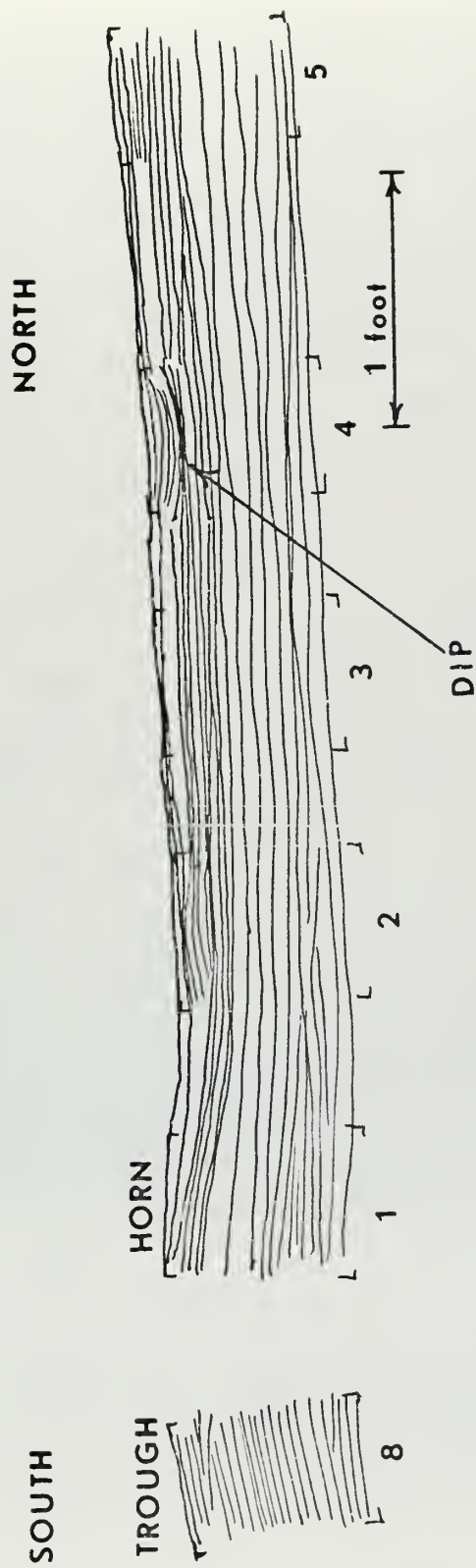


Figure 32. Radiographic analysis of 6 X-rays from Oct 18, 1970,
Sequence No. 2.



East

West

Figure 33. Photograph of impregnation No. 6, Oct 18, 1970, Sequence No. 1 (10% size reduction).



Figure 34. Radiograph of impregnation No. 6, Oct 18, 1970, Sequence No. 1 (actual size).



East

West

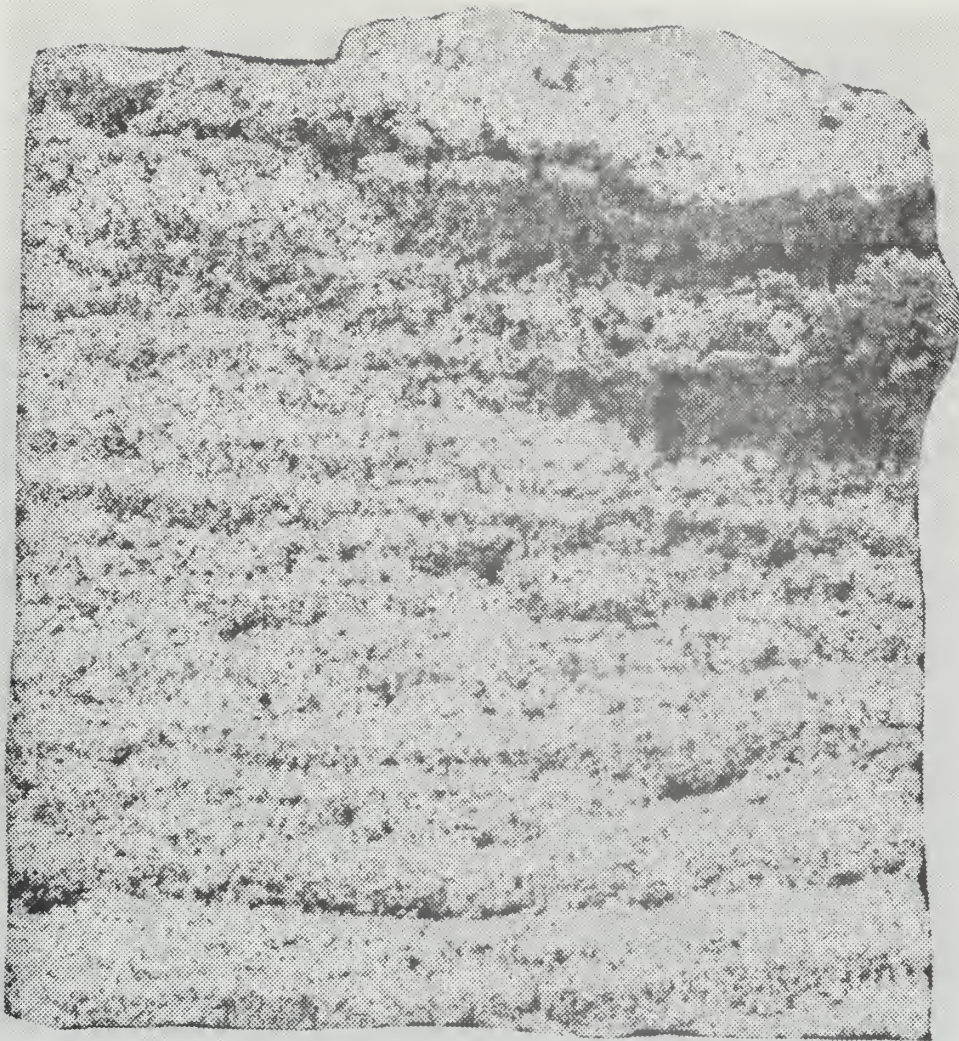
Figure 35. Photograph of impregnation No. 7, Oct 18, 1970, Sequence No. 1 (10% size reduction).



East

West

Figure 36. Radiograph of impregnation No. 7, Oct 18, 1970, Sequence No. 1 (actual size).



East

West

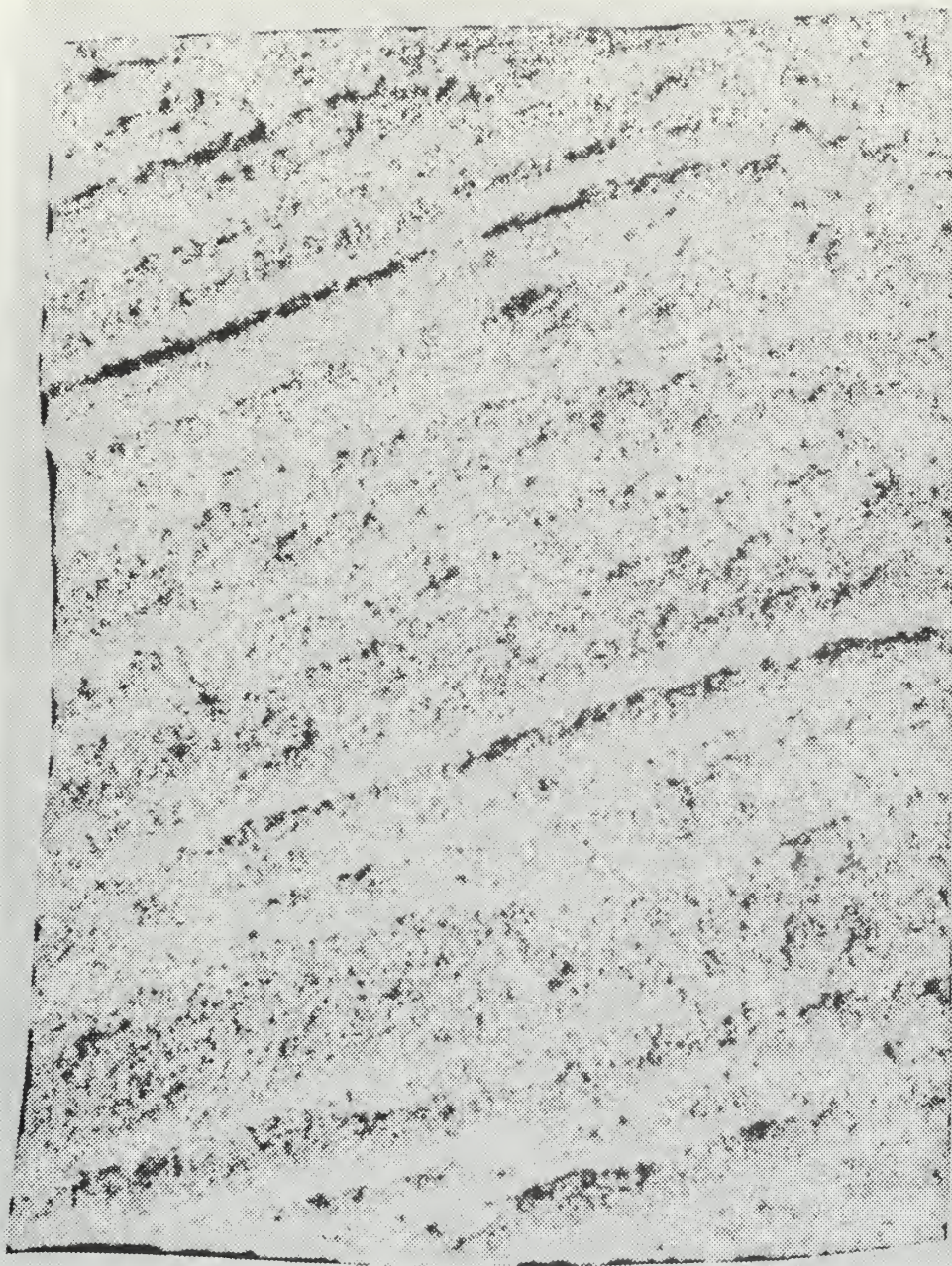
Figure 37. Photograph of impregnation No. 9, Oct 18, 1970, Sequence No. 1 (10% size reduction).



East

West

Figure 38. Radiograph of impregnation No. 9, Oct 18, 1970, Sequence No. 1 (actual size).



East

West

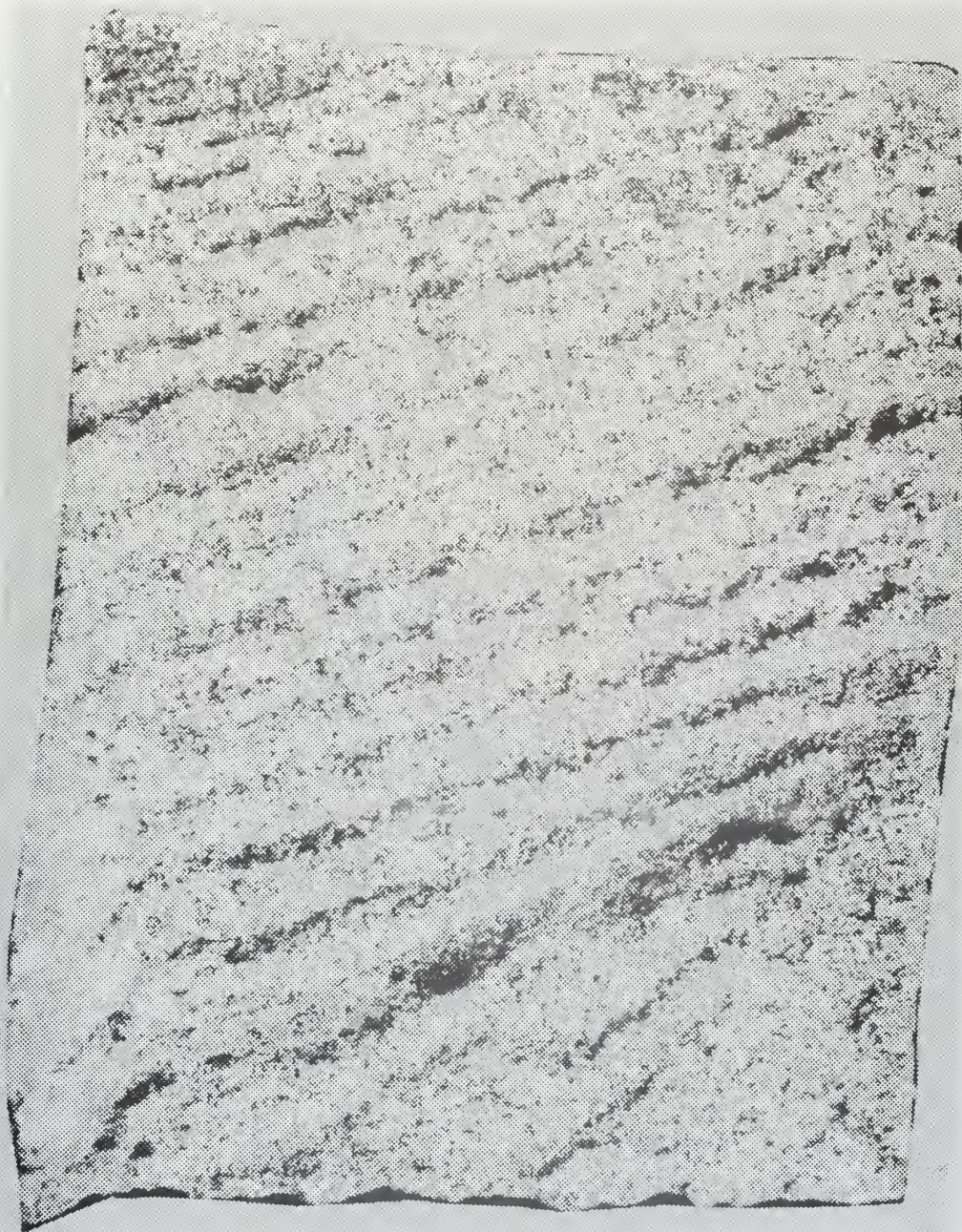
Figure 39. Photograph of impregnation No. 10, Oct 18, 1970, Sequence No. 1 (10% size reduction).



East

West

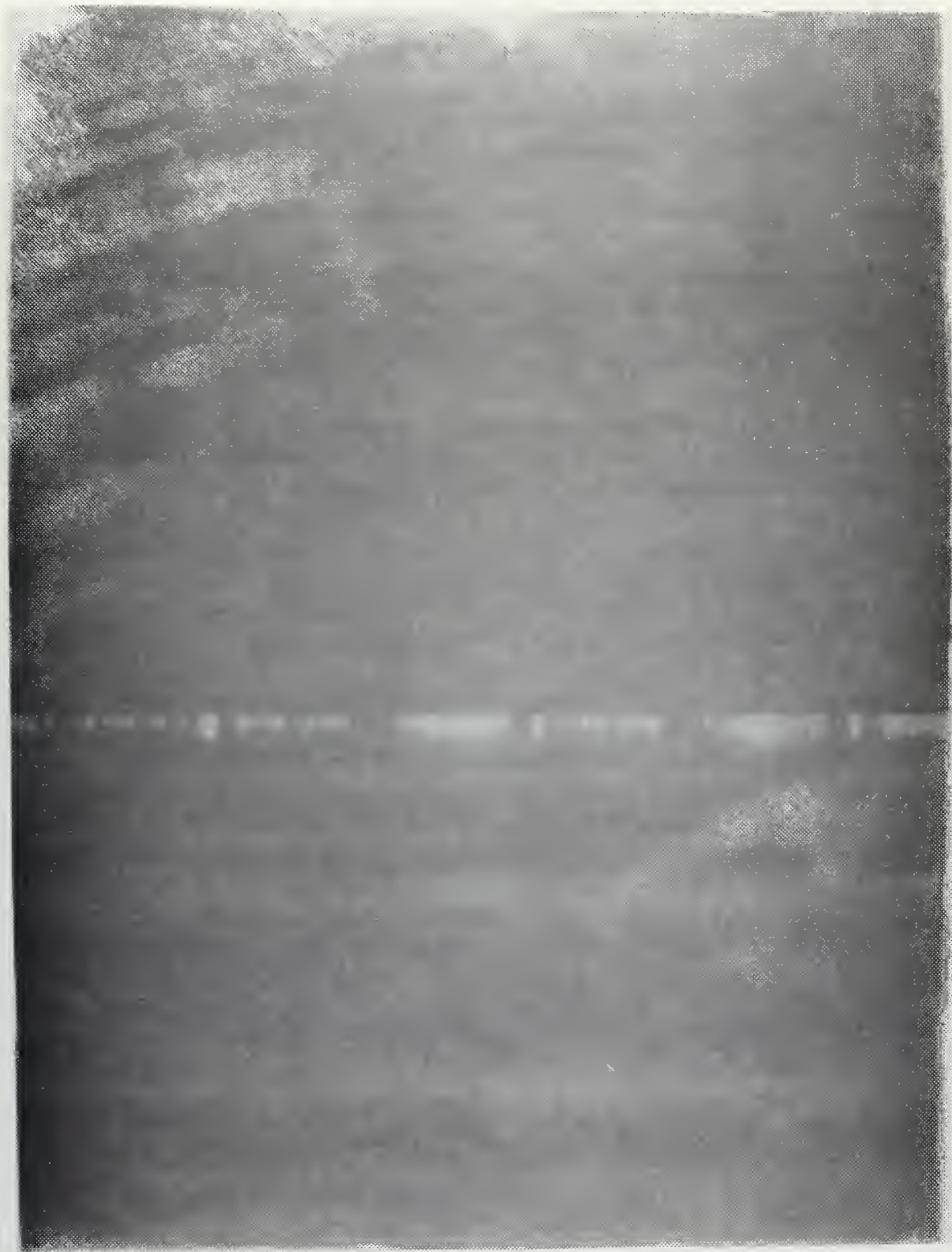
Figure 40. Radiograph of impregnation No. 10, Oct 18, 1970, Sequence No. 1 (actual size).



East

West

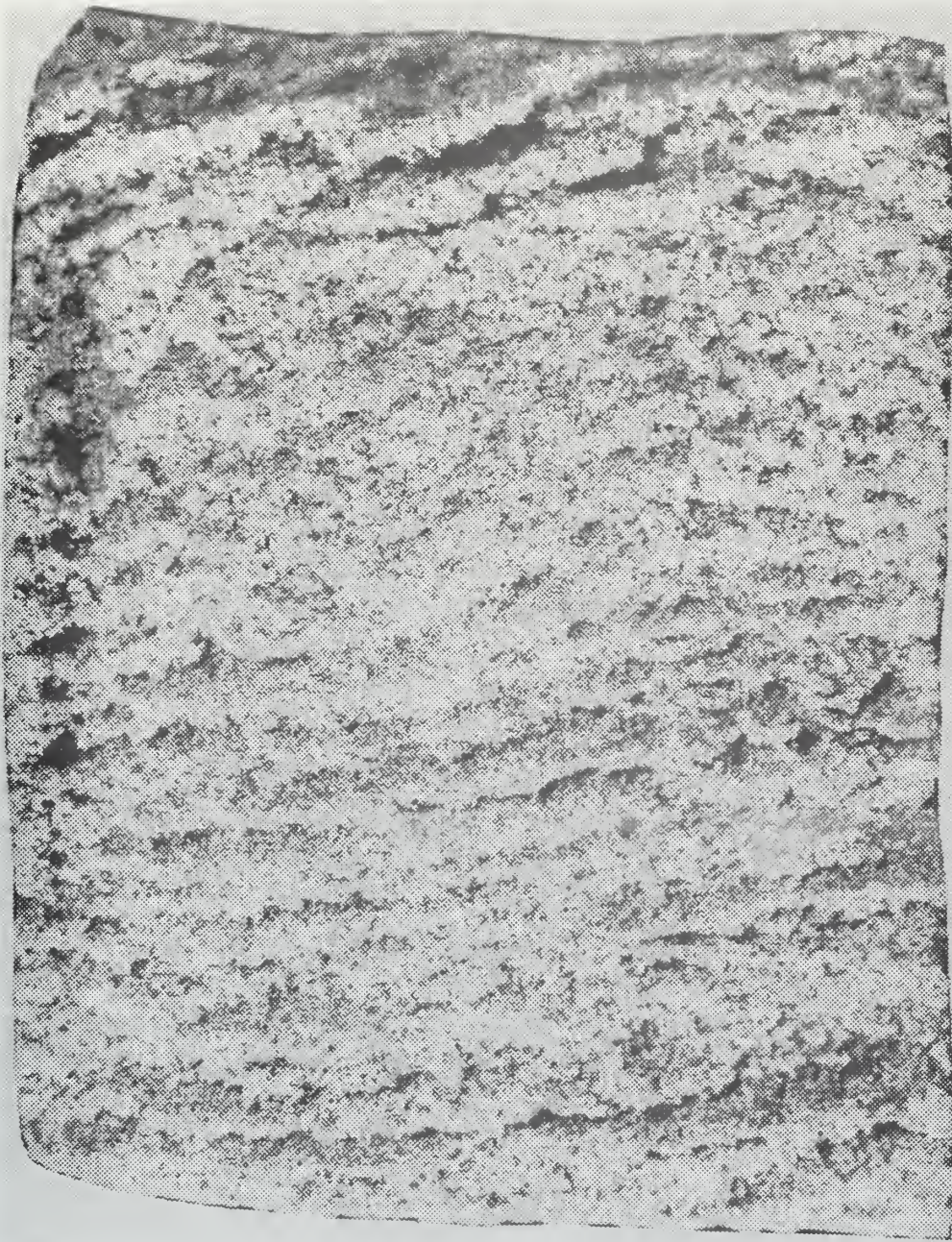
Figure 41. Photograph of impregnation No. 11, Oct 18, 1970, Sequence No. 1 (10% size reduction).



East

West

Figure 42. Radiograph of impregnation No. 11, Oct 18, 1970, Sequence No. 1 (actual size).



East

West

Figure 43. Photograph of impregnation No. 12, Oct 18, 1970, Sequence No. 1 (10% size reduction).



East

West

Figure 44. Radiograph of impregnation No. 12, Oct 18, 1970, Sequence No. 1 (actual size).

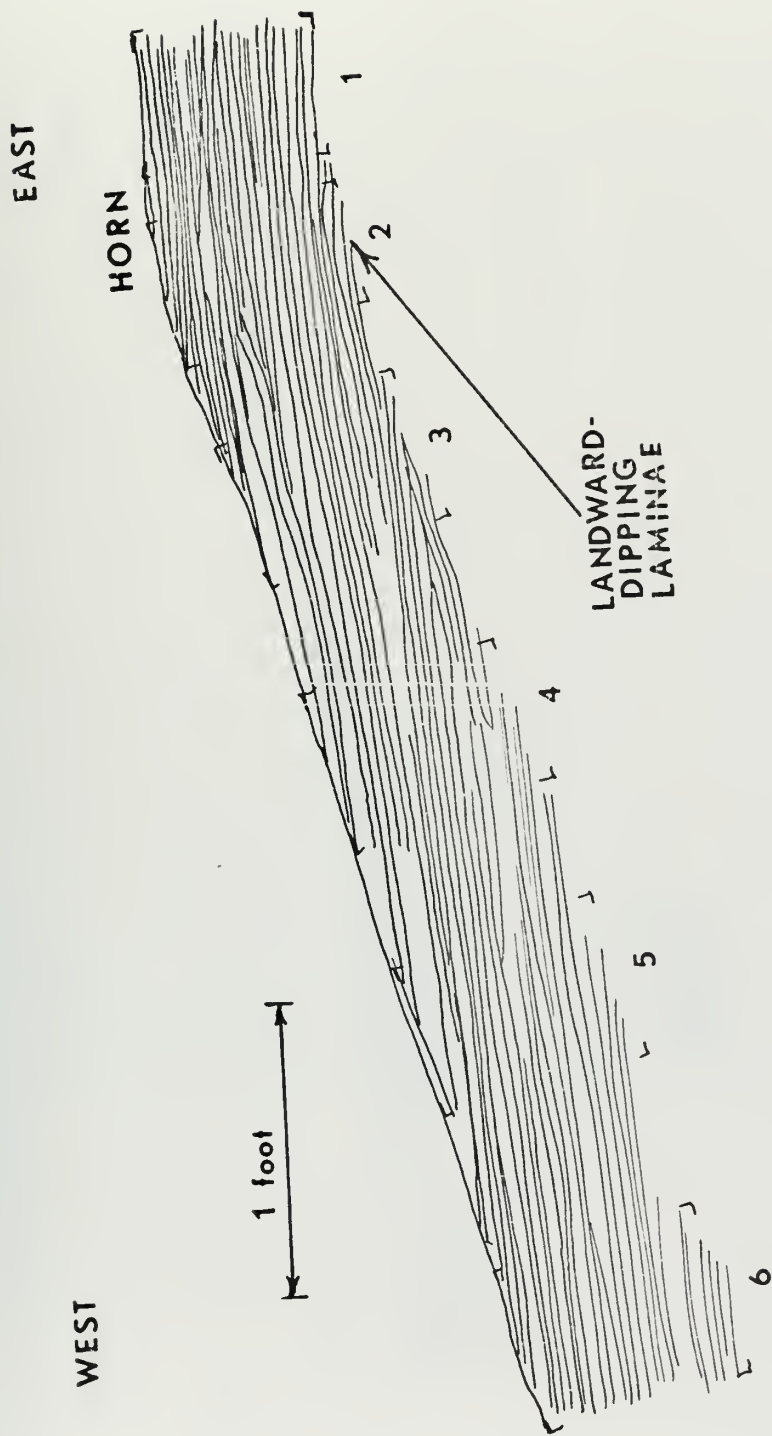


Figure 45. Radiographic analysis of 6 X-rays from
Oct 30, 1970, Sequence No. 3.

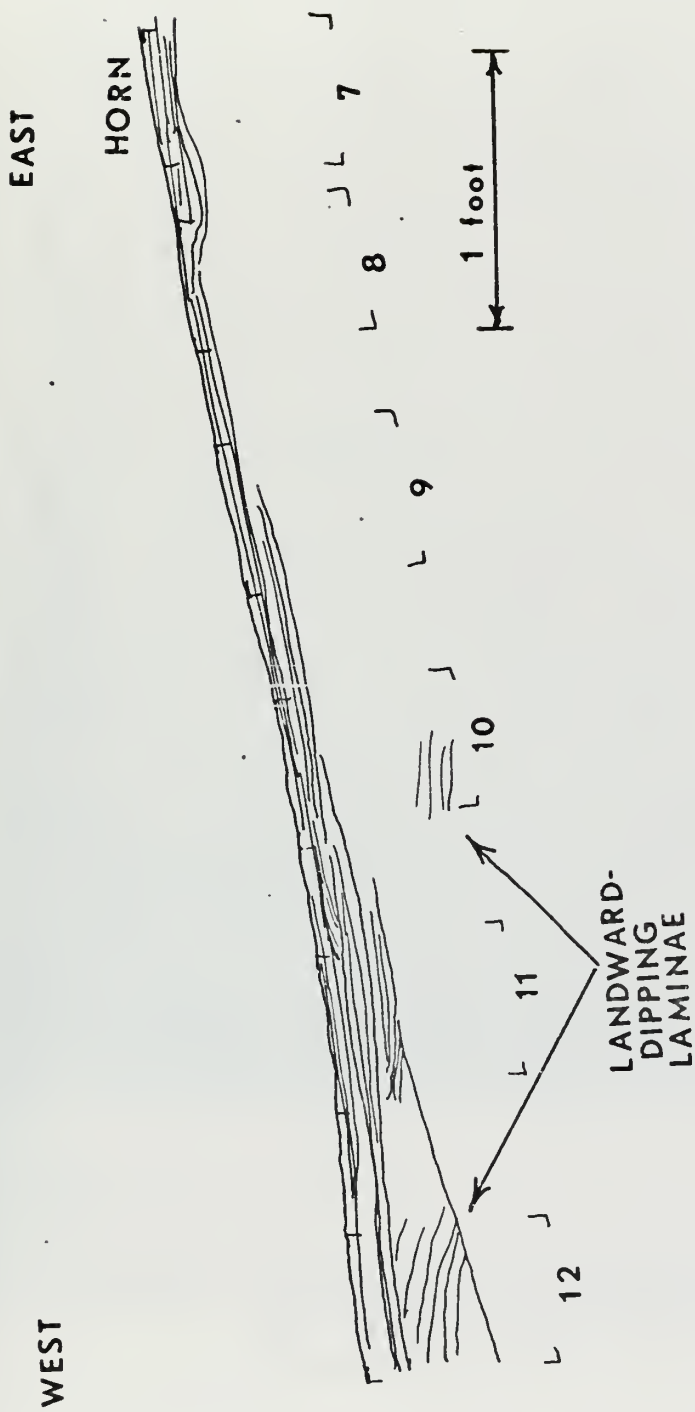


Figure 46. Radiographic analysis of 6 X-rays from
Oct 31, 1970, Sequence No. 4.



East

West

Figure 47. Photograph of impregnation No. 10, Oct 31, 1970, Sequence No. 4 (10% size reduction).



East

West

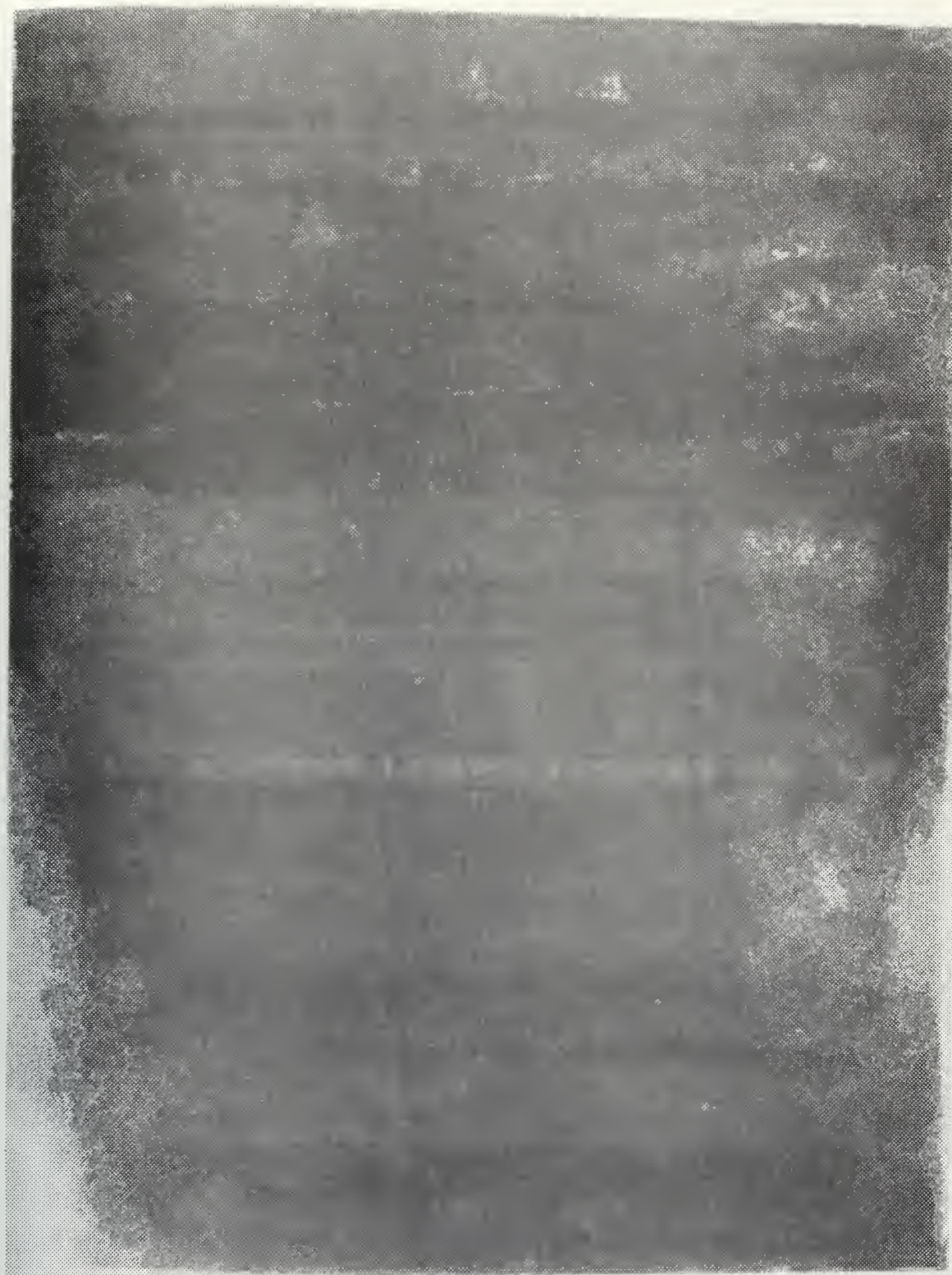
Figure 48. Radiograph of impregnation No. 10, Oct 31, 1970, Sequence No. 4 (actual size).



East

West

Figure 49. Photograph of impregnation No. 11, Oct 31, 1970, Sequence No. 4 (10% size reduction).



East

West

Figure 50. Radiograph of impregnation No. 11, Oct 31, 1970, Sequence No. 4 (actual size).

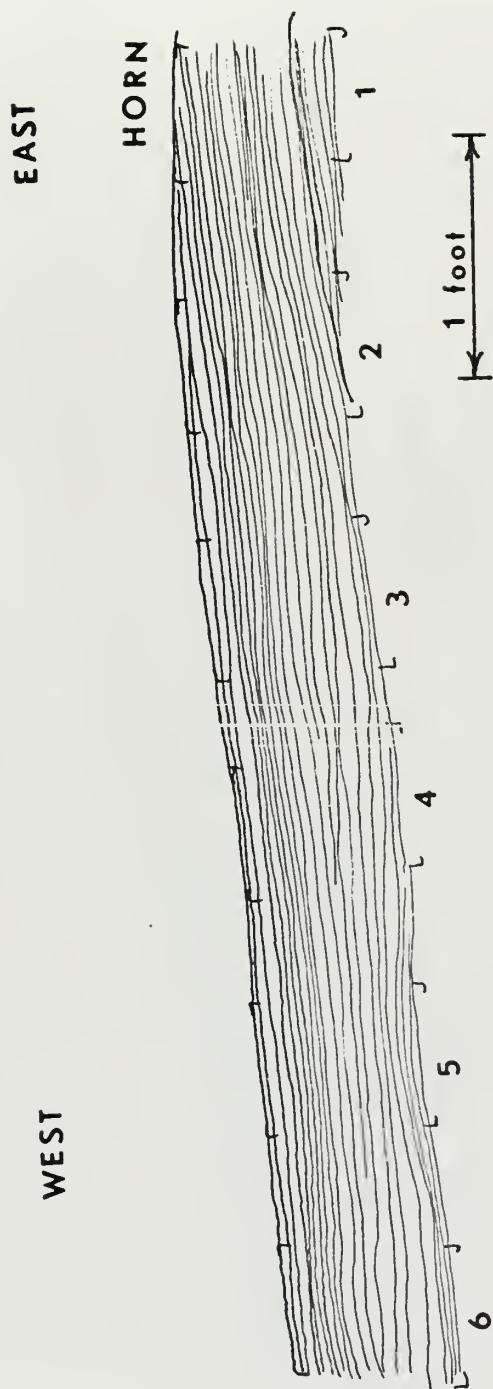


Figure 51. Radiographic analysis of 6 X-rays from
Nov 5, 1970, Sequence No. 5.

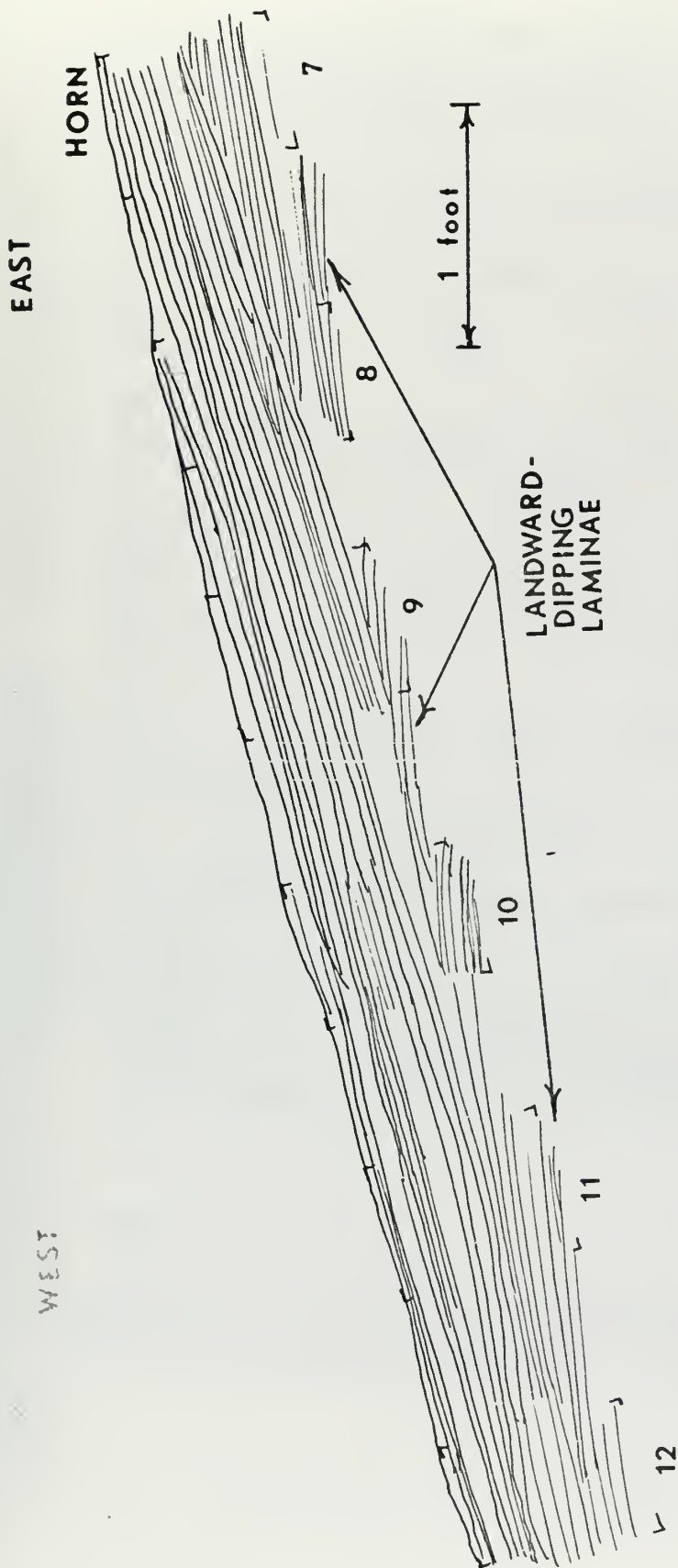
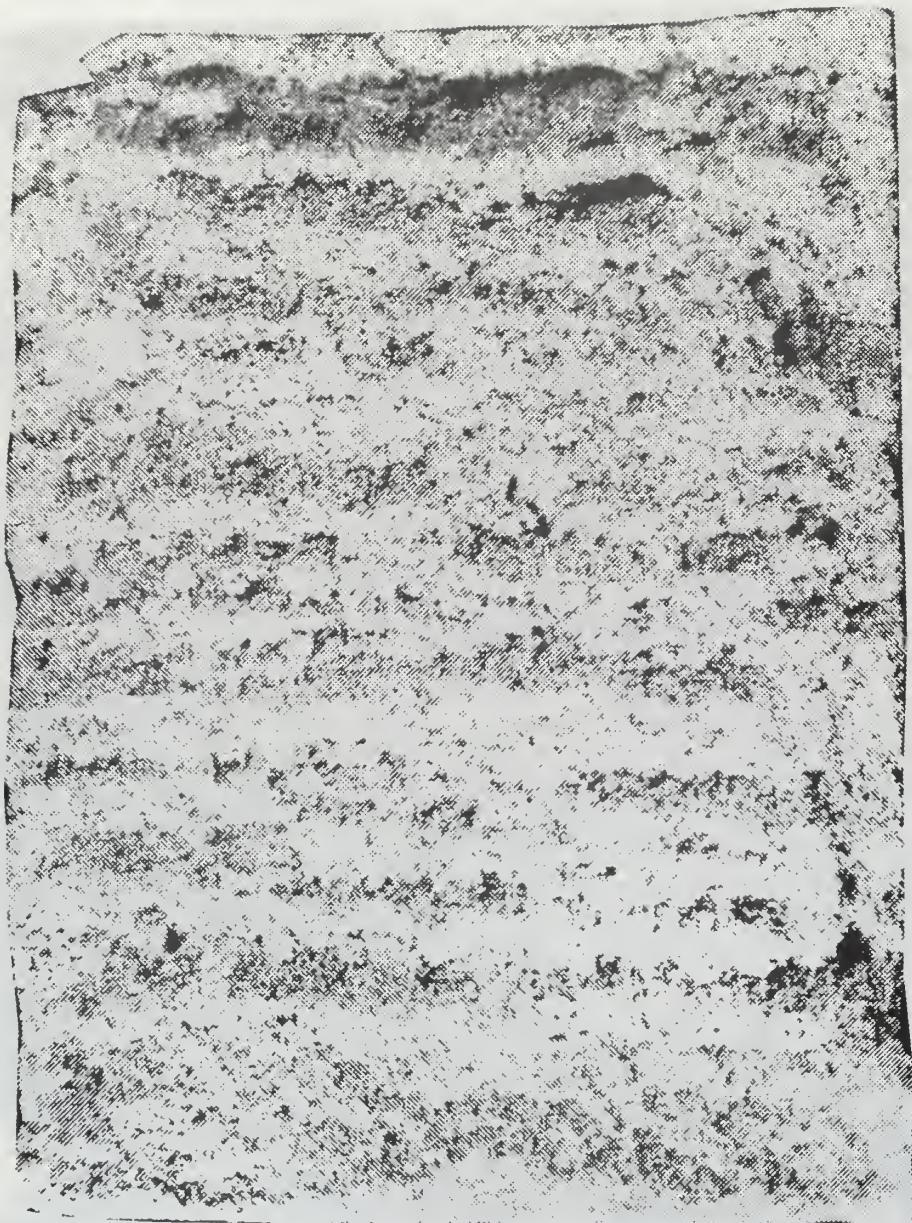


Figure 52. Radiographic analysis of 6 X-rays from
Nov 6, 1970, Sequence No. 6.



East

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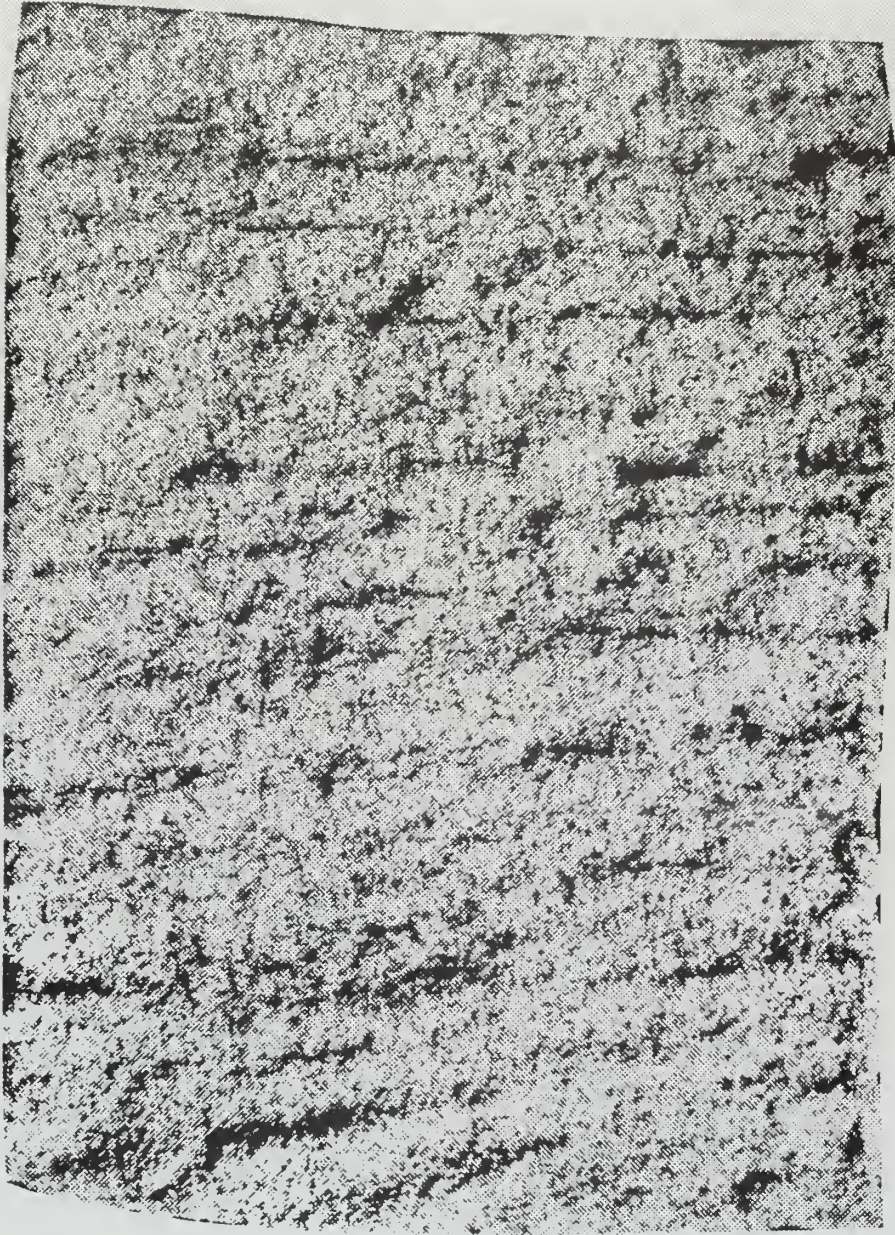
Figure 53. Photograph of impregnation No. 9, Nov 6, 1970, Sequence No. 6 (10% size reduction).



East

West

Figure 54. Radiograph of impregnation No. 9, Nov 6, 1970, Sequence No. 6 (actual size).



East

West

Figure 55. Photograph of impregnation No. 10, Nov 6, 1970, Sequence No. 6 (10% size reduction).



East

West

Figure 56. Radiograph of impregnation No. 10, Nov 6, 1970, Sequence No. 6 (actual size).

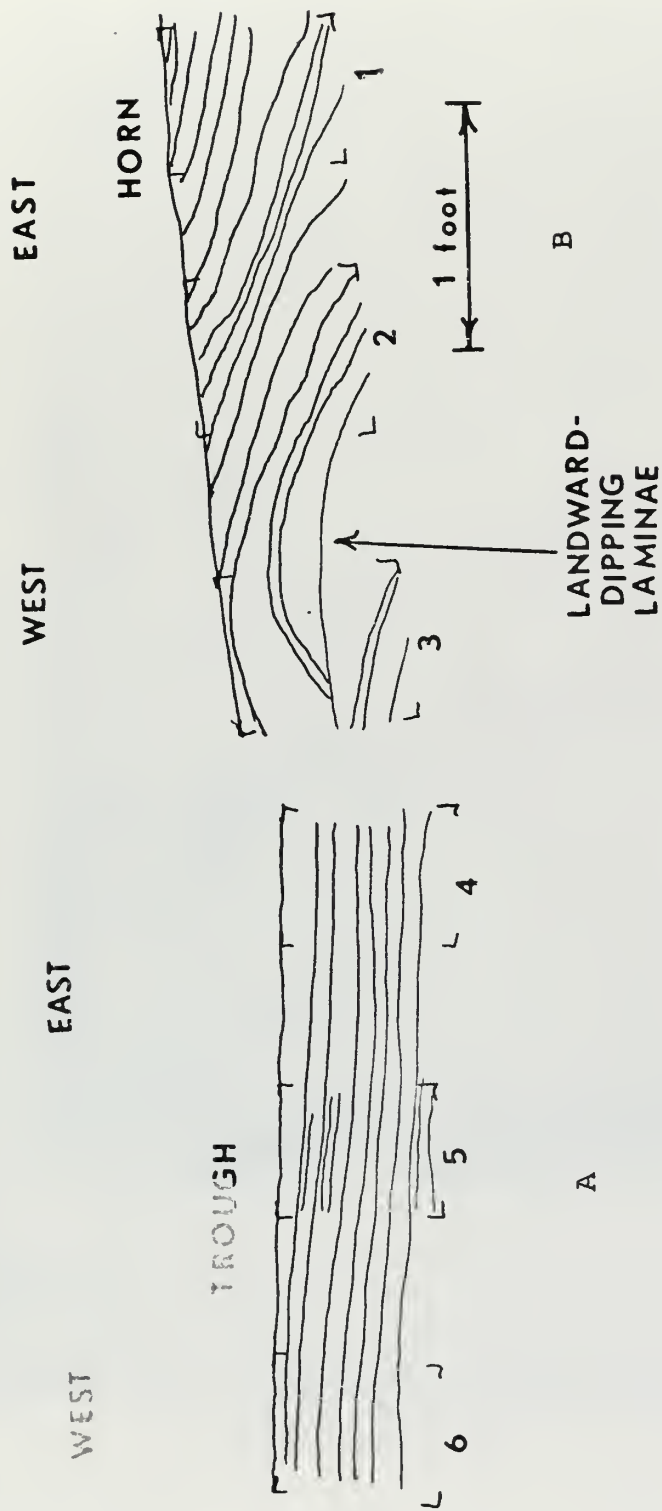


Figure 57. Radiographic analysis of 6 X-rays from
Nov 9, 1970, Sequence No. 7.



East

West

Figure 58. Photograph of impregnation No. 1, Nov 9, 1970, Sequence No. 7 (10% size reduction).



East

West

Figure 59. Radiograph of impregnation No. 1, Nov 9, 1970, Sequence No. 7 (actual size).



East

West

Figure 60. Photograph of impregnation No. 2, Nov 9, 1970, Sequence No. 7 (10% size reduction).



East

West

Figure 61. Radiograph of impregnation No. 2, Nov 9, 1970, Sequence No. 7 (actual size).

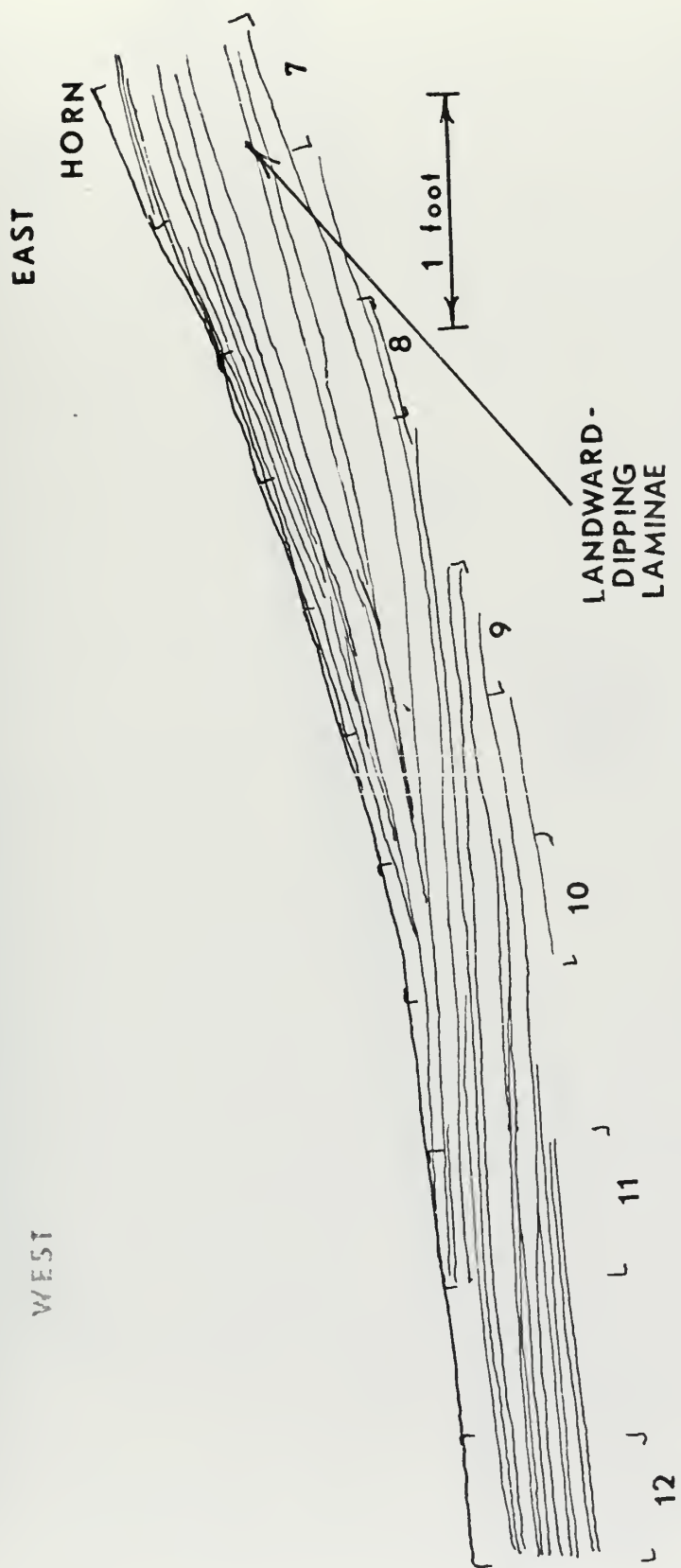


Figure 62. Radiographic analysis of 6 X-rays from
Nov 10, 1970, Sequence No. 8.

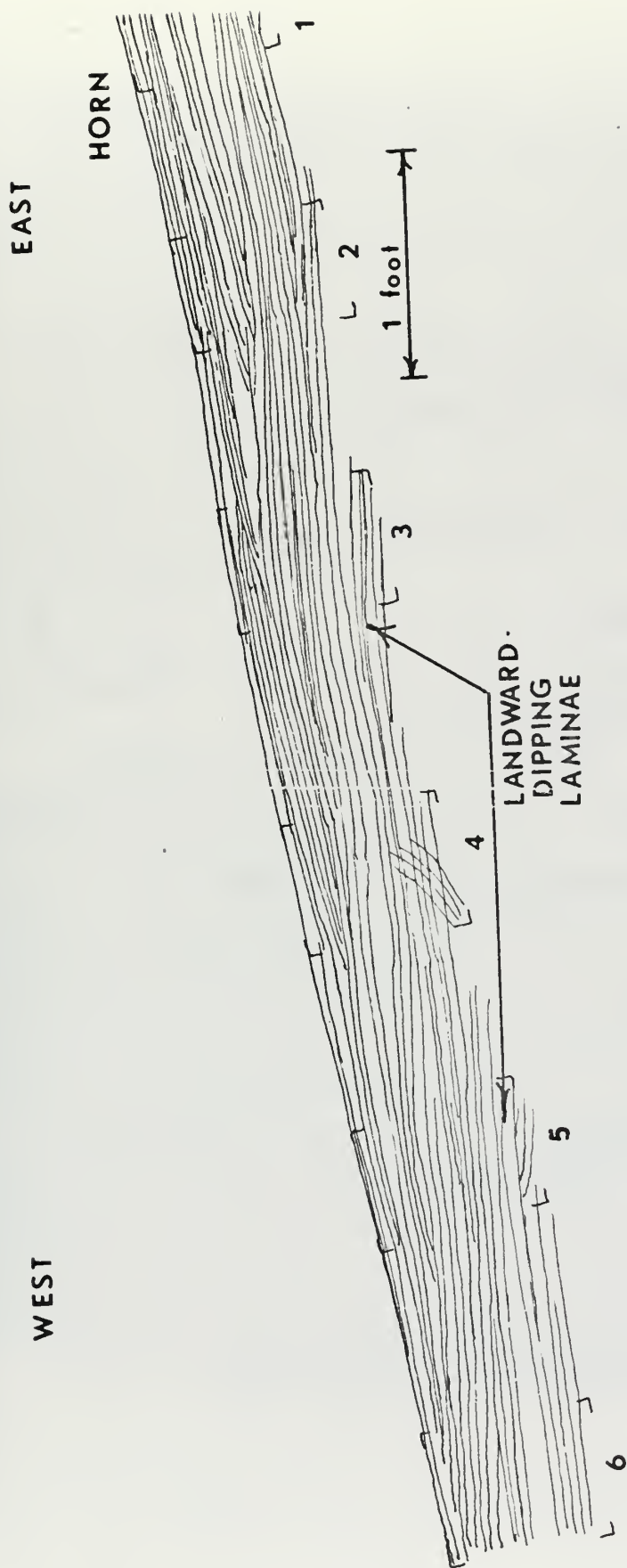
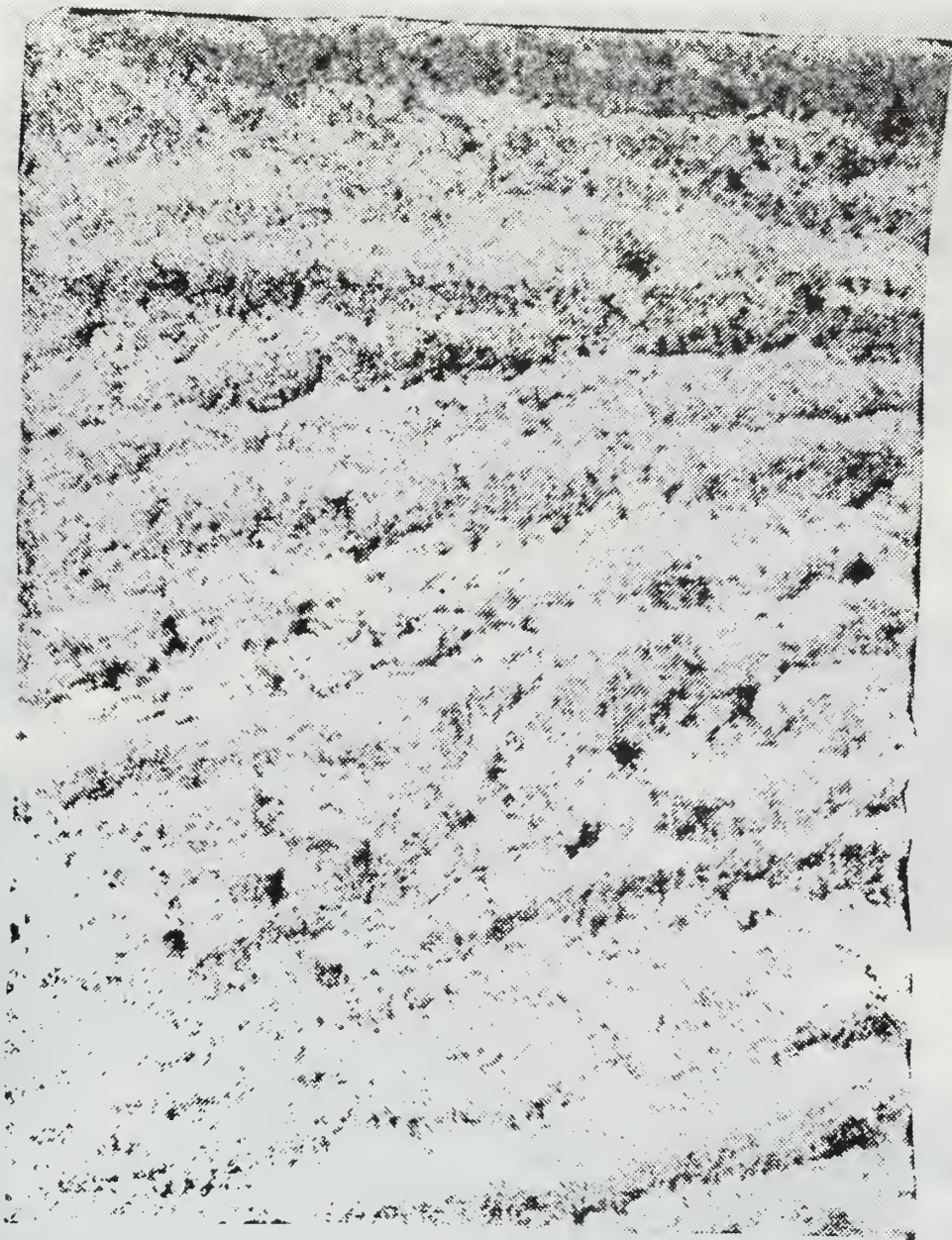


Figure 63. Radiographic analysis of 6 X-rays from
Nov 16, 1970, Sequence No. 9.



East

West

Figure 64. Photograph of impregnation No. 3, Nov 16, 1970, Sequence No. 9 (10% size reduction).



East

West

Figure 65. Radiograph of impregnation No. 3, Nov 16, 1970, Sequence No. 9 (actual size).

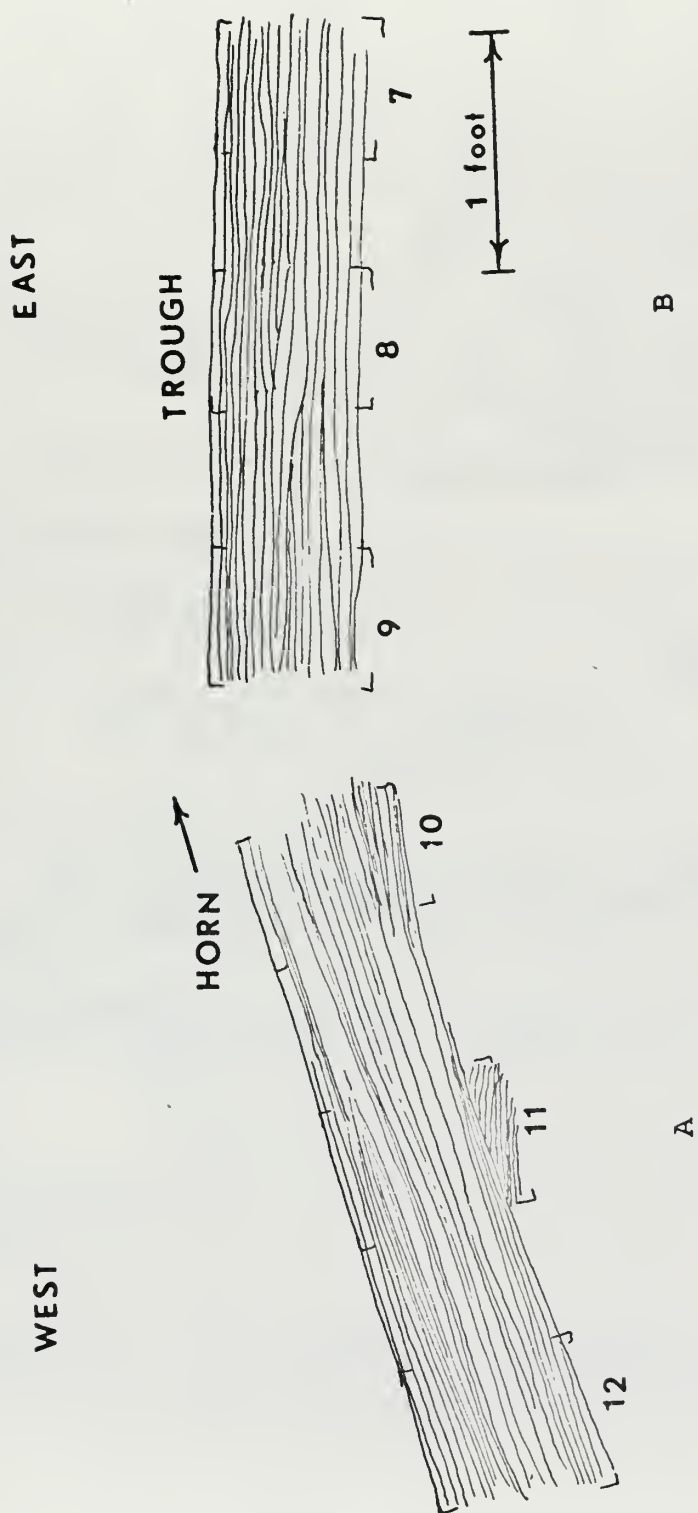


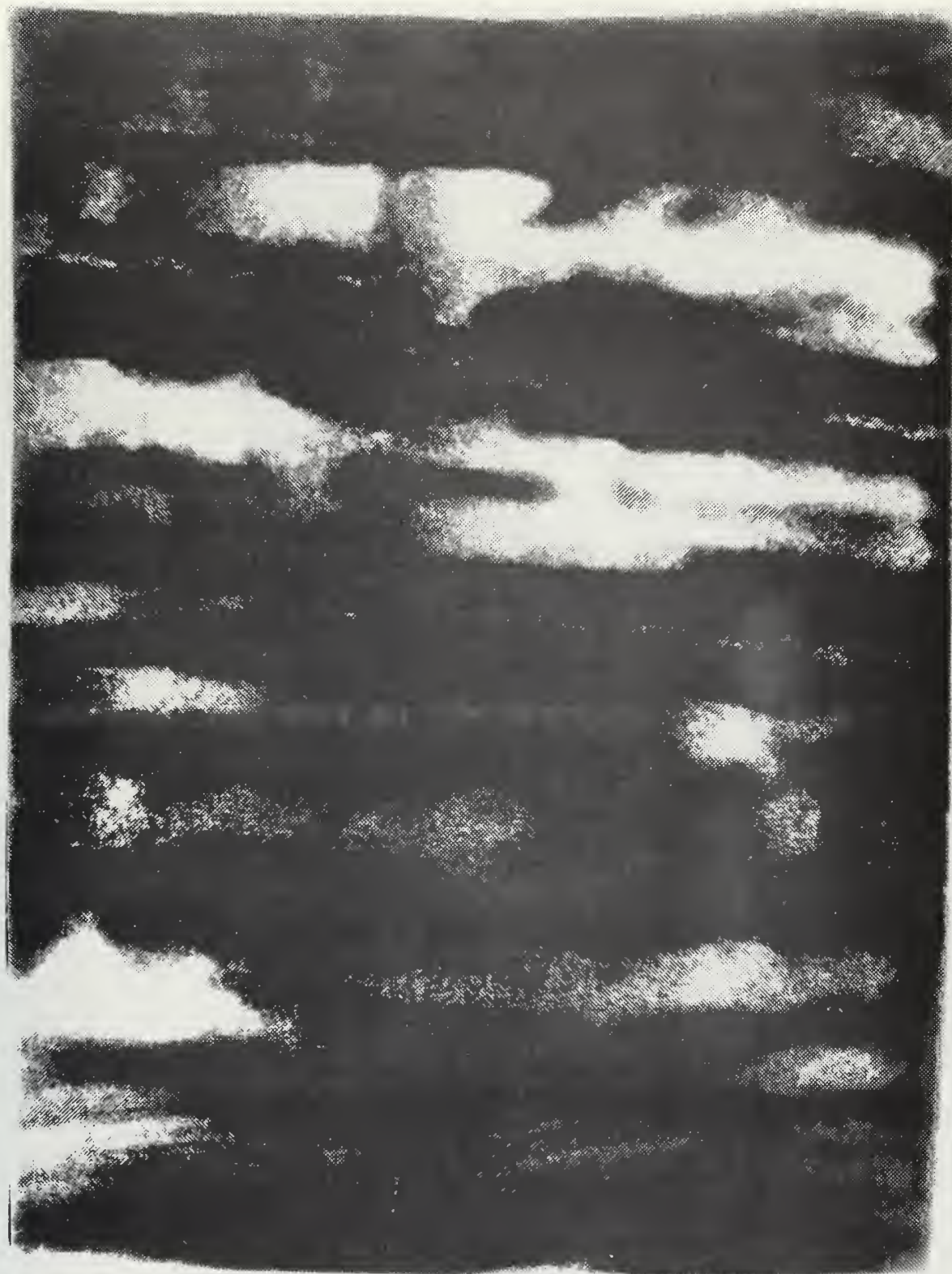
Figure 66. Radiographic analysis of 6 X-rays from
Nov 17, 1970, Sequence No. 10.



East

West

Figure 67. Photograph of impregnation No. 11, Nov 17, 1970, Sequence No. 10 (10% size reduction).



East

West

Figure 68. Radiograph of impregnation No. 11, Nov 17, 1970, Sequence No. 10 (actual size).

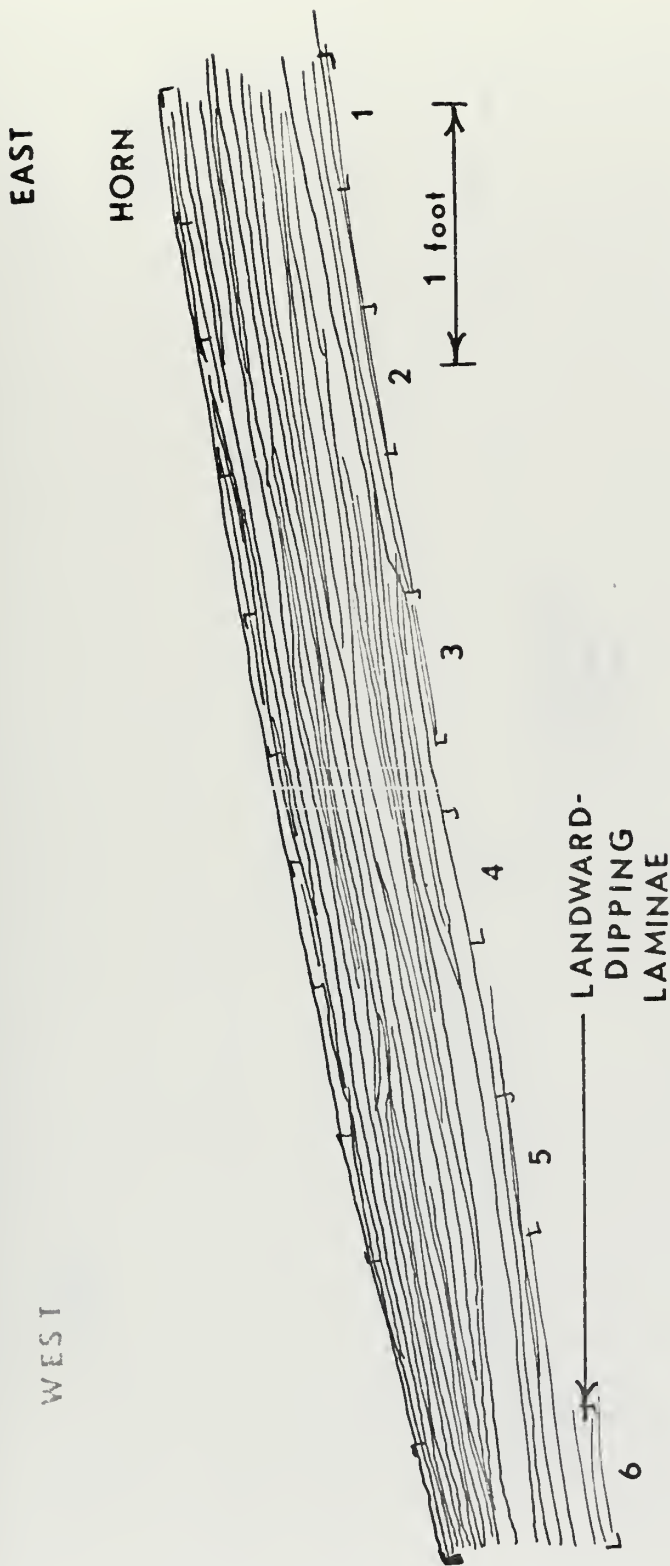


Figure 69. Radiographic analysis of 6 X-rays from
Nov 20, 1970, Sequence No. 11.

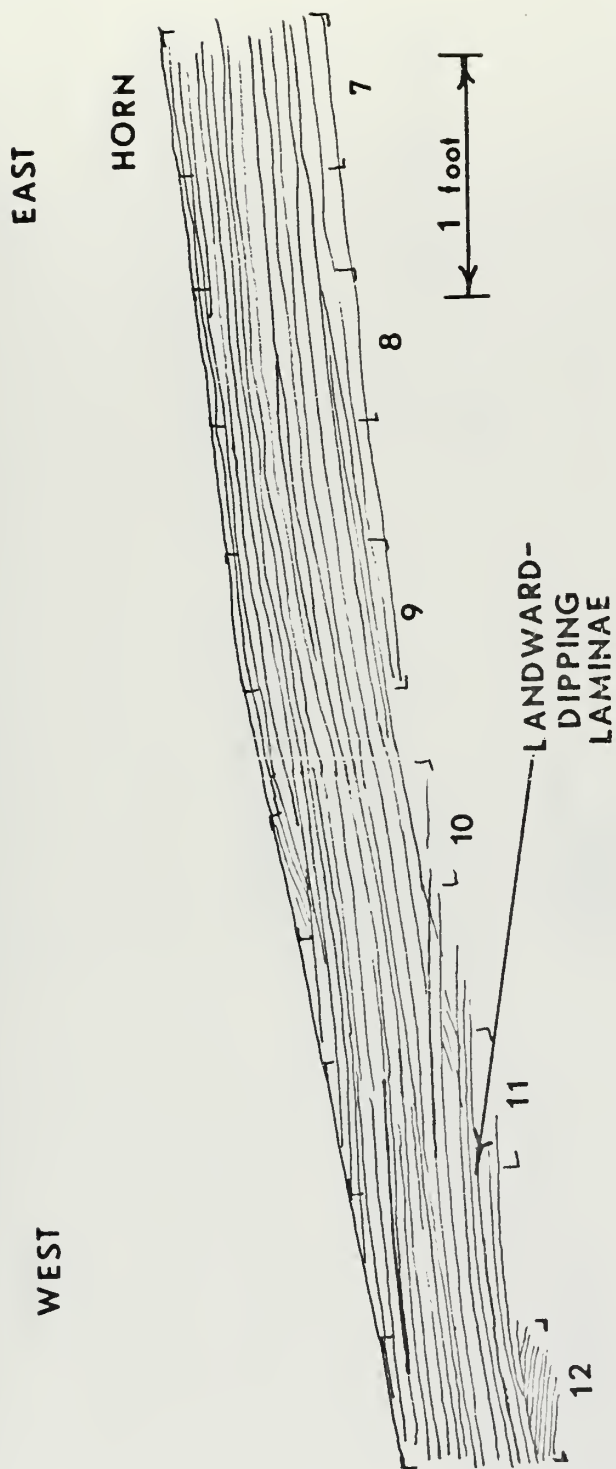


Figure 70. Radiographic analysis of 6 X-rays from
Nov 21, 1970, Sequence No. 12.

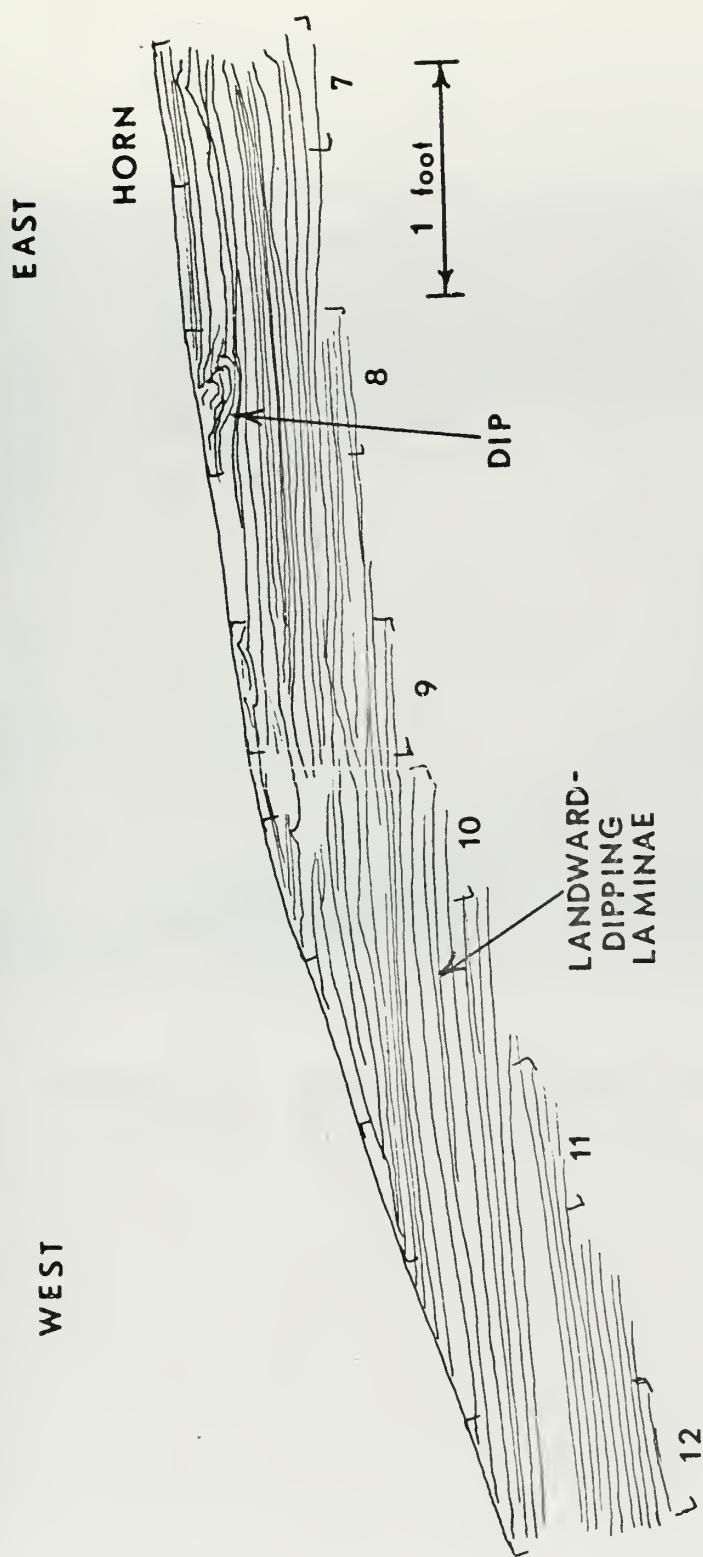


Figure 71. Radiographic analysis of 6 X-rays from Jan 23, 1971, Sequence No. 13.



Figure 72. Cusp profile after one tidal cycle
on Jan 27, 1971.



Figure 73. Initial stake arrangement used on Jan 28, 1971.

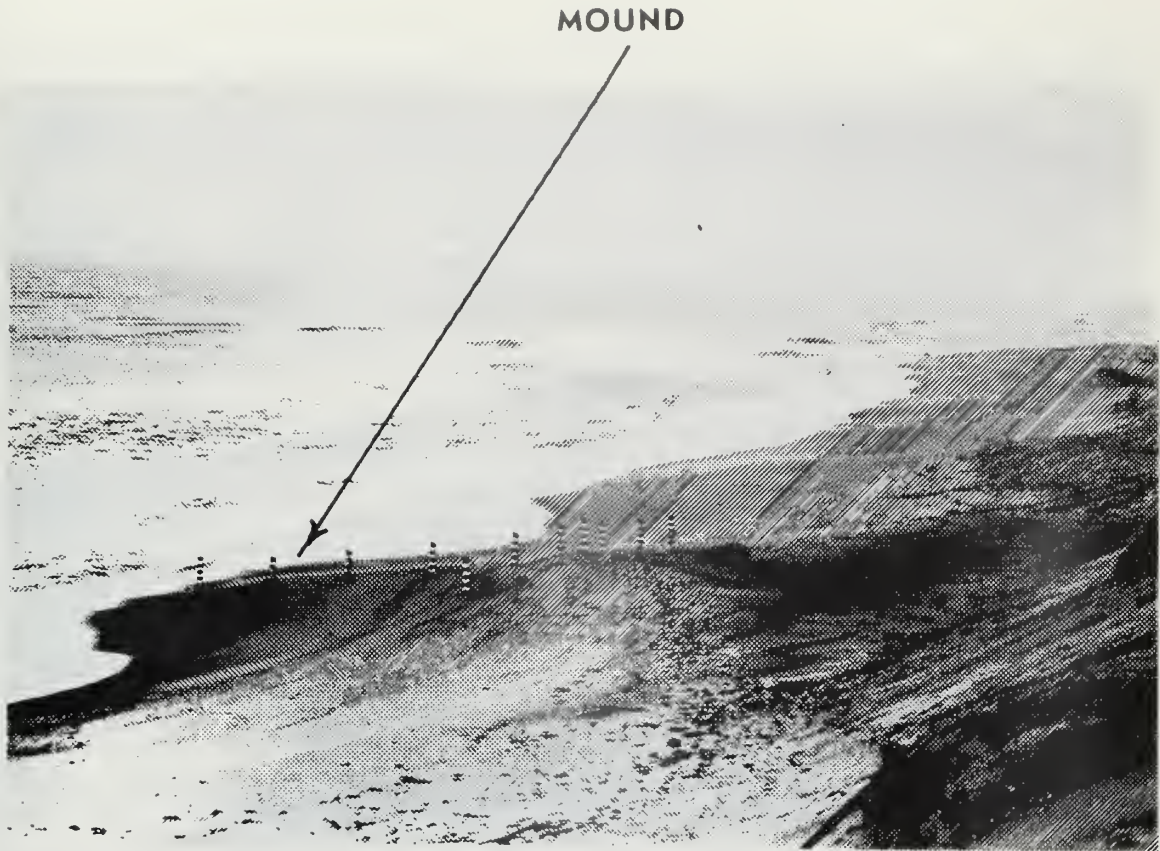


Figure 74. Cusp profile at 9:00 a.m.,
Jan 28, 1971.

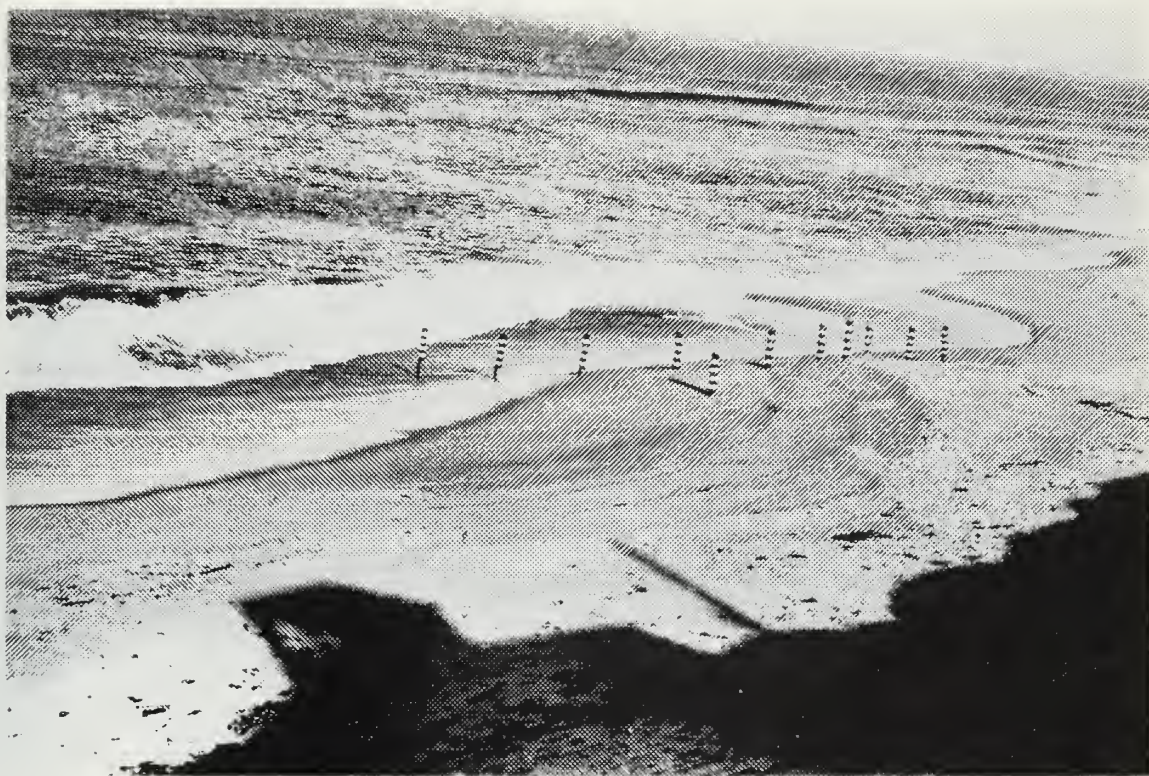


Figure 75. Cusp profile at 10:00 a.m.,
Jan 28, 1971.



Figure 76. Cusp profile at 11:12 a.m.,
Jan 28, 1971.

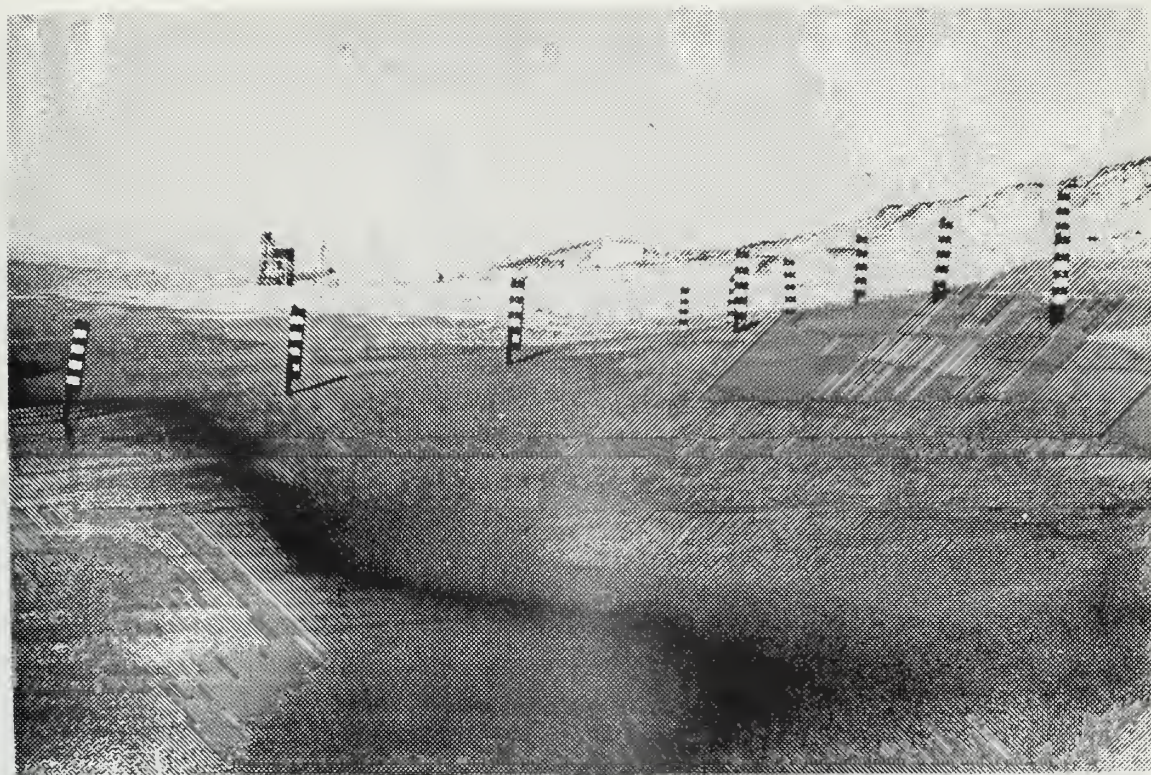


Figure 77. Cusp profile at 4:00 p.m.,
Jan 28, 1971.

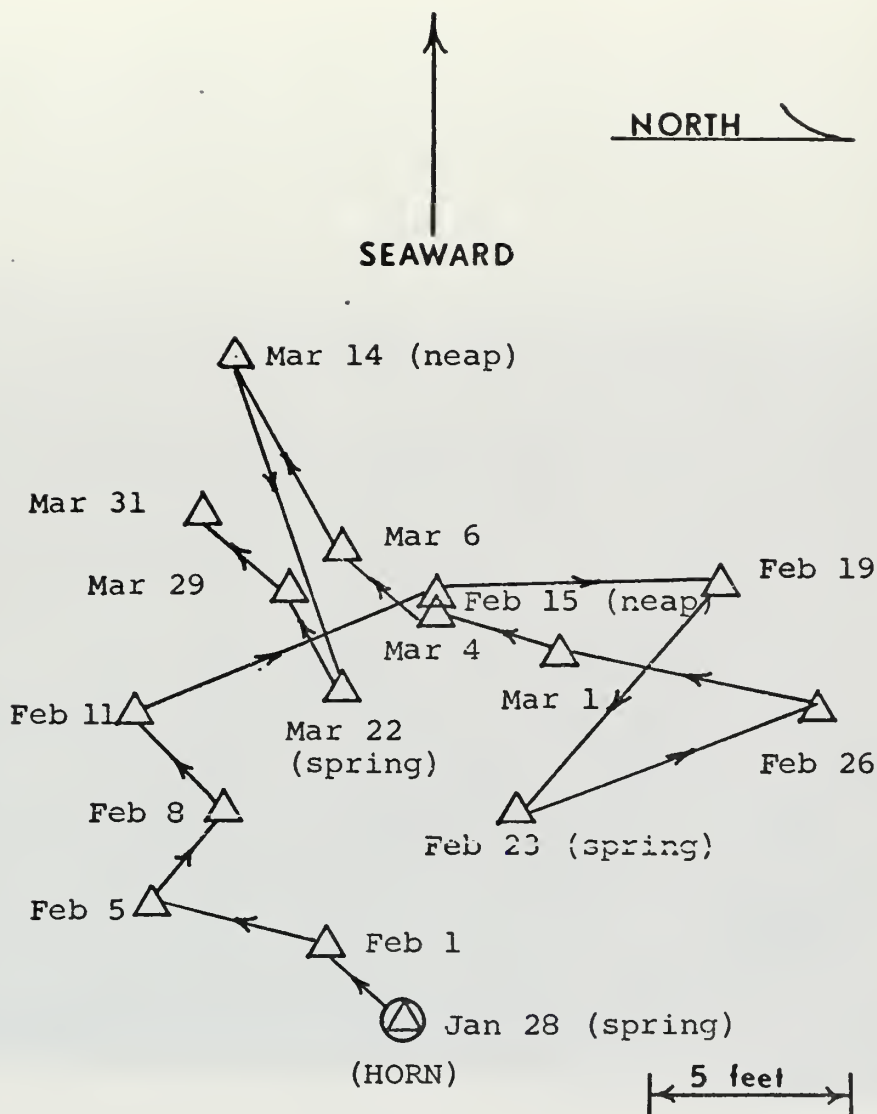


Figure 78. Cusp horn migration map
(accurate to ± 2 in).

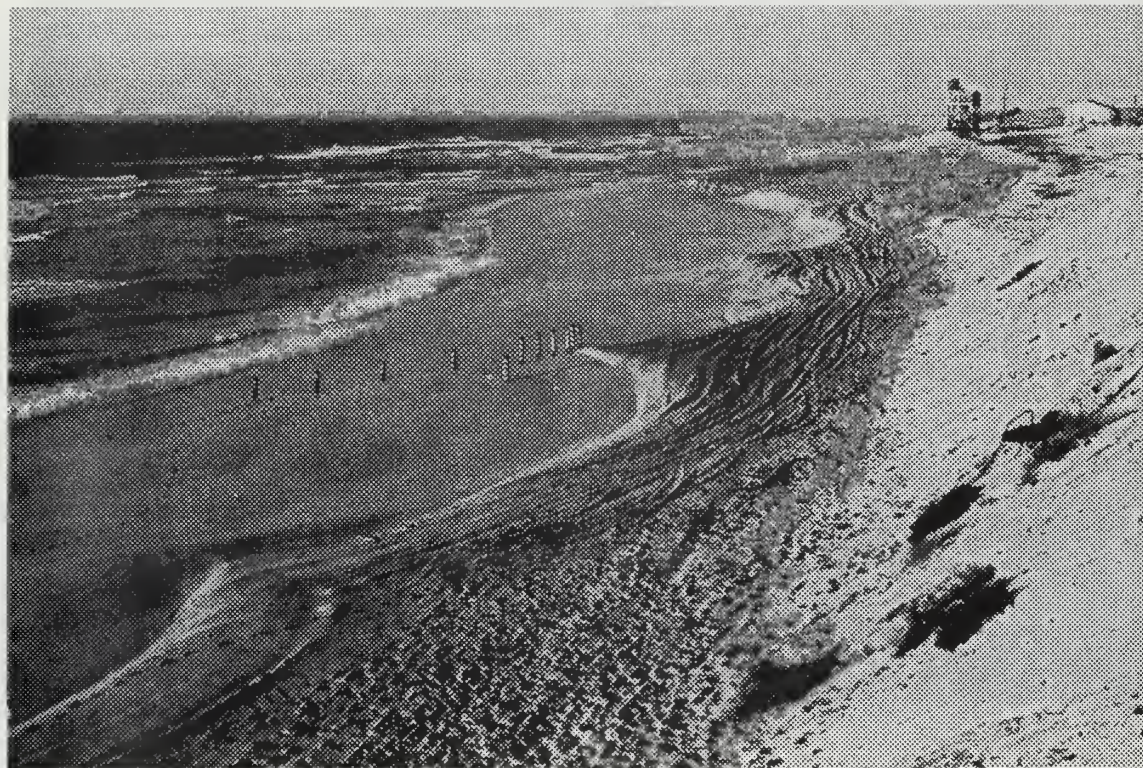


Figure 79. Scarping of cusp after calm weather. (Jan 30, 1971).



Figure 80. Trough swash marks.



Figure 81. Horn swash marks.

APPENDIX A

IMPREGNATION MATERIALS

Resin Specifications:

Brand name: "Sea Jay"

Type: Polyester Resin

Quantity: Available in one to 25 gallon lots--five gallon cans were found to be ideal for this study.

Manufacturer: C. J. Hendry Co.

(Main Office) 139 Townsend Street
San Francisco, California
Telephone: DOuglas 2-4242

(Branch Office) 111-121 Front Street
San Pedro, California
Telephone: TErminal 2-0281
(or)
2607 Byron Street
San Diego, California
Telephone: ACademy 3-1691

Resin Hardener:

Brand name: "Sea Jay"

Quantity: 2-ounce plastic bottles--a sufficient supply is furnished with the purchase of the resin.

Manufacturer: Sarafan Corporation
San Francisco, California

Acetone (used for cleaning solvent):

Brand name: "Sea Jay"

Quantity: One gallon cans were found adequate for this study.

APPENDIX B

X-RAY PROCESSING SPECIFICATIONS

X-ray Film:

Manufacturer: Eastman Kodak Co.
Rochester, New York

Type: No-Screen tinted Estar Safety Base
Medical X-ray Film
NS-2T
Ready Pack with rounded corners

Size: Eight by ten inches

X-ray Processing Liquid:

Manufacturer: Eastman Kodak Co.
Rochester, New York

Type: (1) Liquid X-ray Developer and
Replenisher (one quart makes a
gallon of developer)

(2) Liquid X-ray Fixer and Replenisher
(one quart makes a gallon of
fixer)

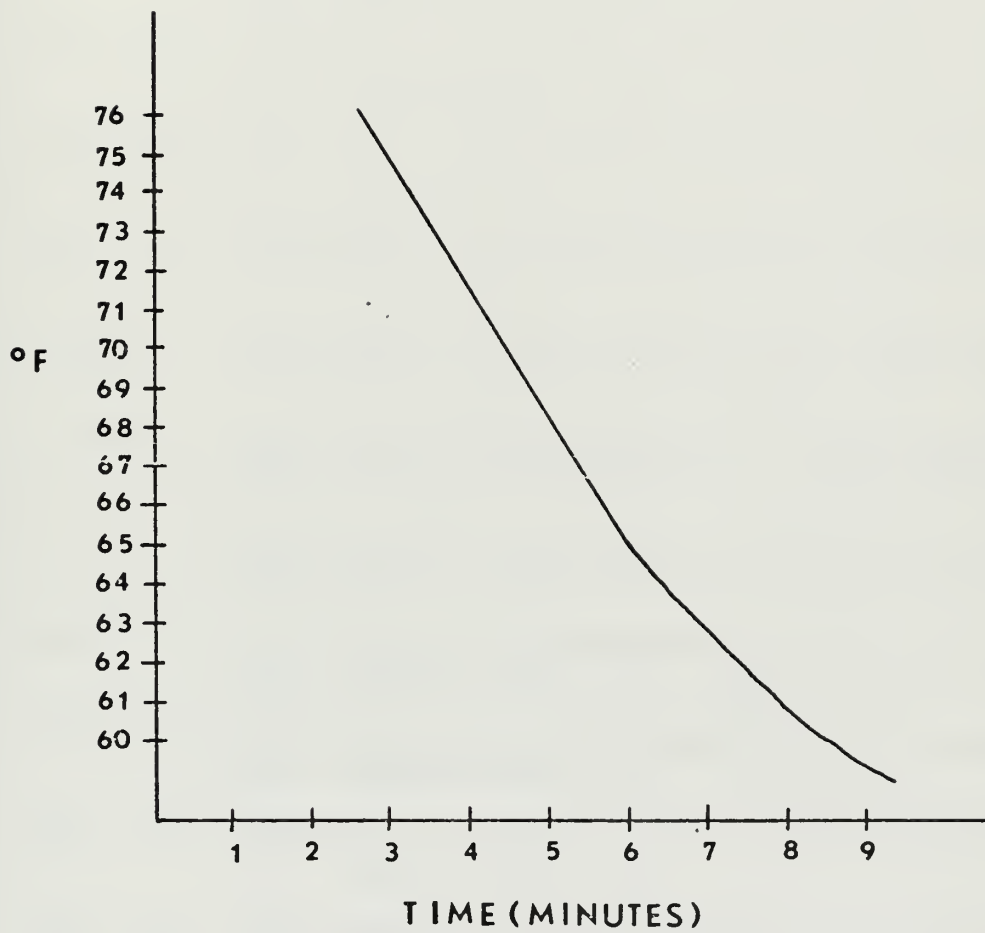


Figure 82. Kodak X-ray film developer time chart.

APPENDIX C

PHOTOGRAPHS AND RADIOGRAPHS OF IMPREGNATIONS TAKEN ON JAN 23, 1971

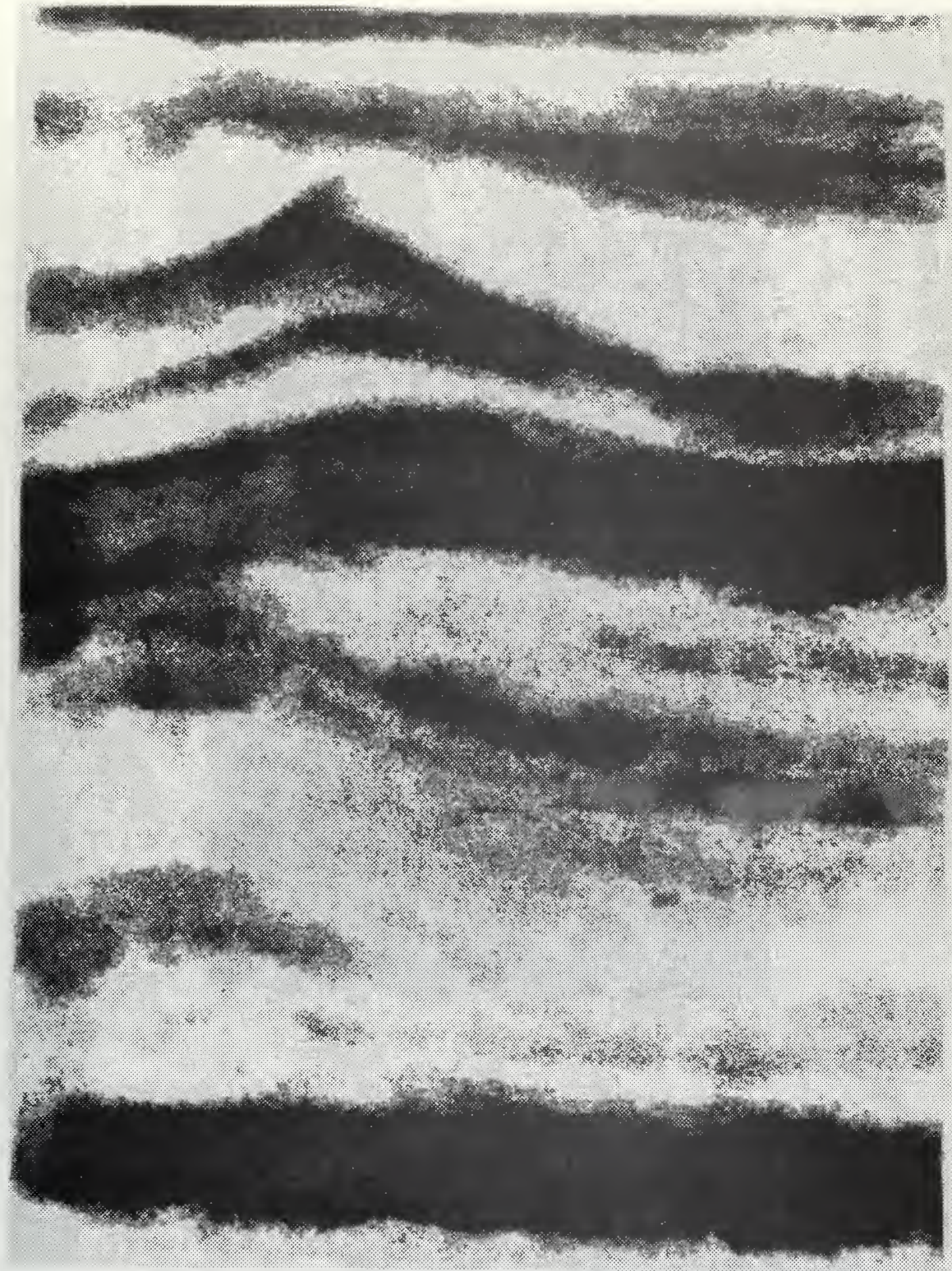
1. Fig. 83: Photograph of impregnation No. 7, Jan 23, 1971, Sequence No. 13.
2. Fig. 84: Radiograph of impregnation No. 7, Jan 23, 1971, Sequence No. 13.
3. Fig. 85: Photograph of impregnation No. 8, Jan 23, 1971, Sequence No. 13.
4. Fig. 86: Radiograph of impregnation No. 8, Jan 23, 1971, Sequence No. 13.
5. Fig. 87: Photograph of impregnation No. 9, Jan 23, 1971, Sequence No. 13.
6. Fig. 88: Radiograph of impregnation No. 9, Jan 23, 1971, Sequence No. 13.
7. Fig. 89: Photograph of impregnation No. 10, Jan 23, 1971, Sequence No. 13.
8. Fig. 90: Radiograph of impregnation No. 10, Jan 23, 1971, Sequence No. 13.
9. Fig. 91: Photograph of impregnation No. 11, Jan 23, 1971, Sequence No. 13.
10. Fig. 92: Radiograph of impregnation No. 11, Jan 23, 1971, Sequence No. 13.
11. Fig. 93: Photograph of impregnation No. 12, Jan 23, 1971, Sequence No. 13.
12. Fig. 94: Radiograph of impregnation No. 12, Jan 23, 1971, Sequence No. 13.



East

West

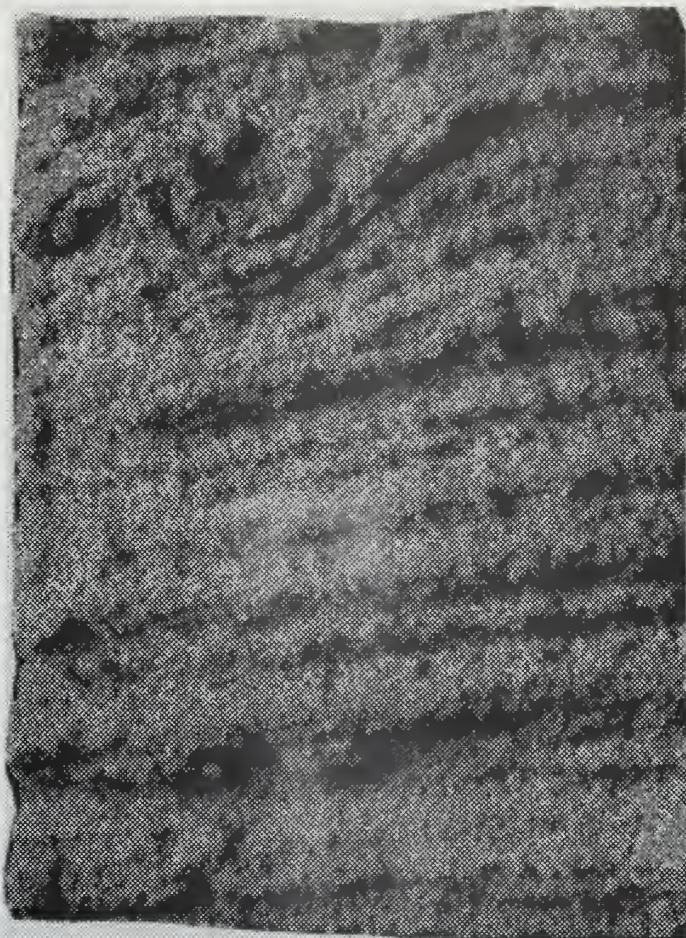
Figure 83. Photograph of impregnation No. 7, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

Figure 84. Radiograph of impregnation No. 7, Jan 23, 1971, Sequence No. 13 (actual size).



East

West

Figure 85. Photograph of impregnation No. 8, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

Figure 86. Radiograph of impregnation No. 8, Jan 23, 1971, Sequence No. 13 (actual size).



East

West

Figure 87. Photograph of impregnation No. 9, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

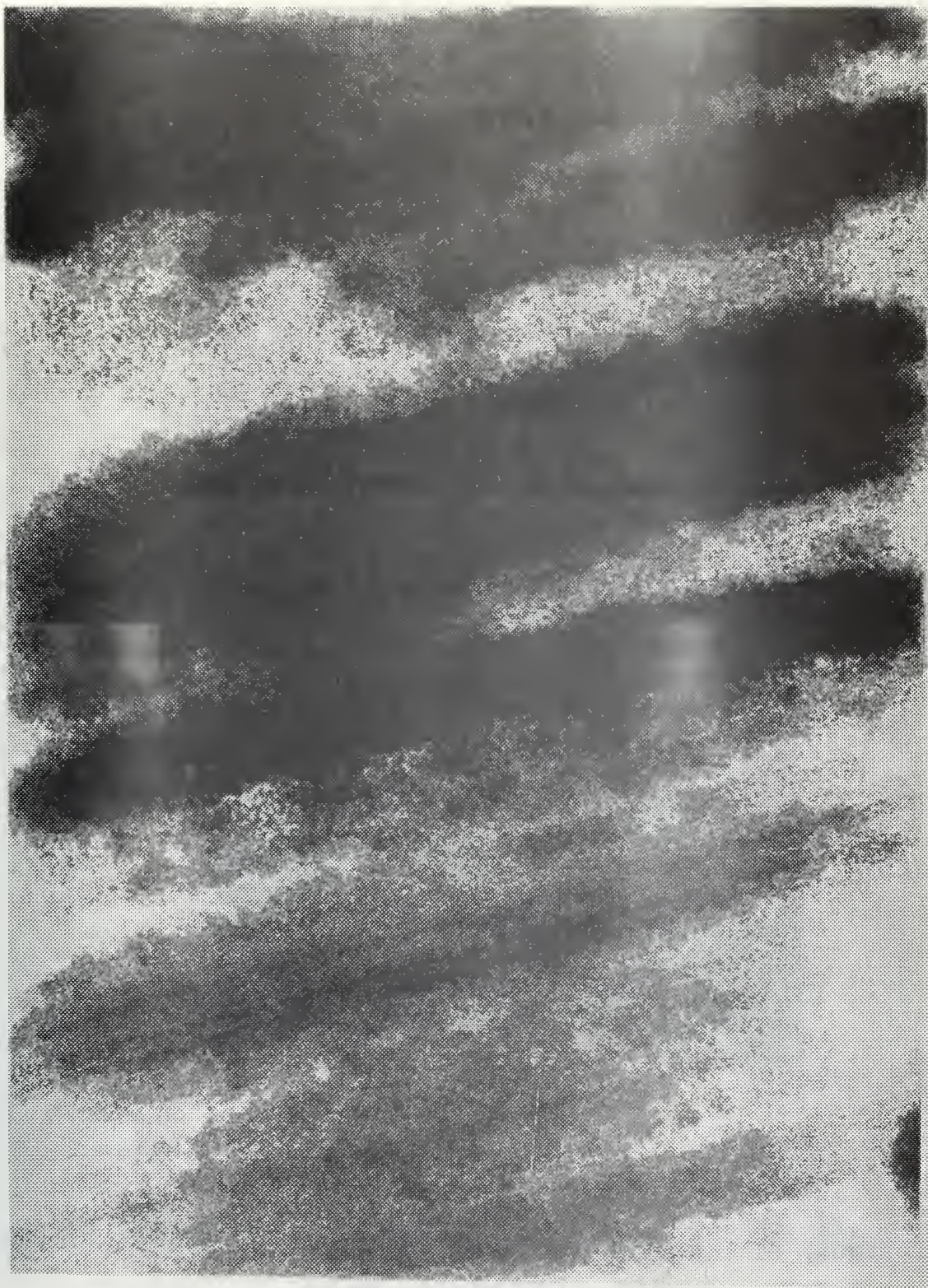
Figure 88. Radiograph of impregnation No. 9, Jan 23, 1971, Sequence No. 13 (actual size).



East

West

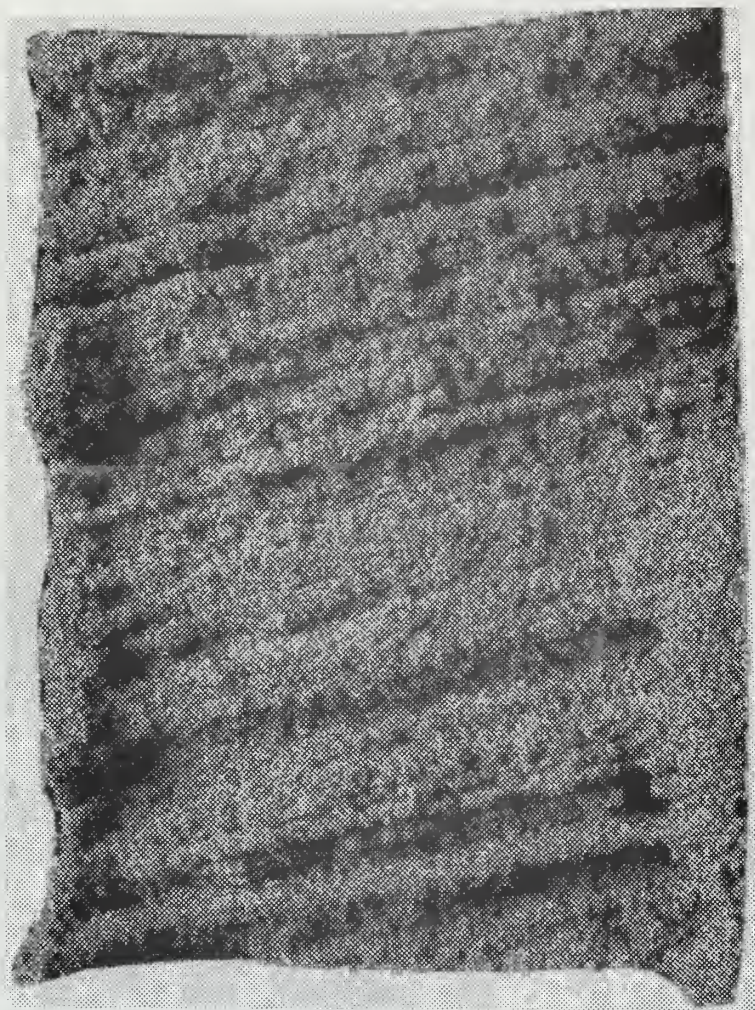
Figure 89. Photograph of impregnation No. 10, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

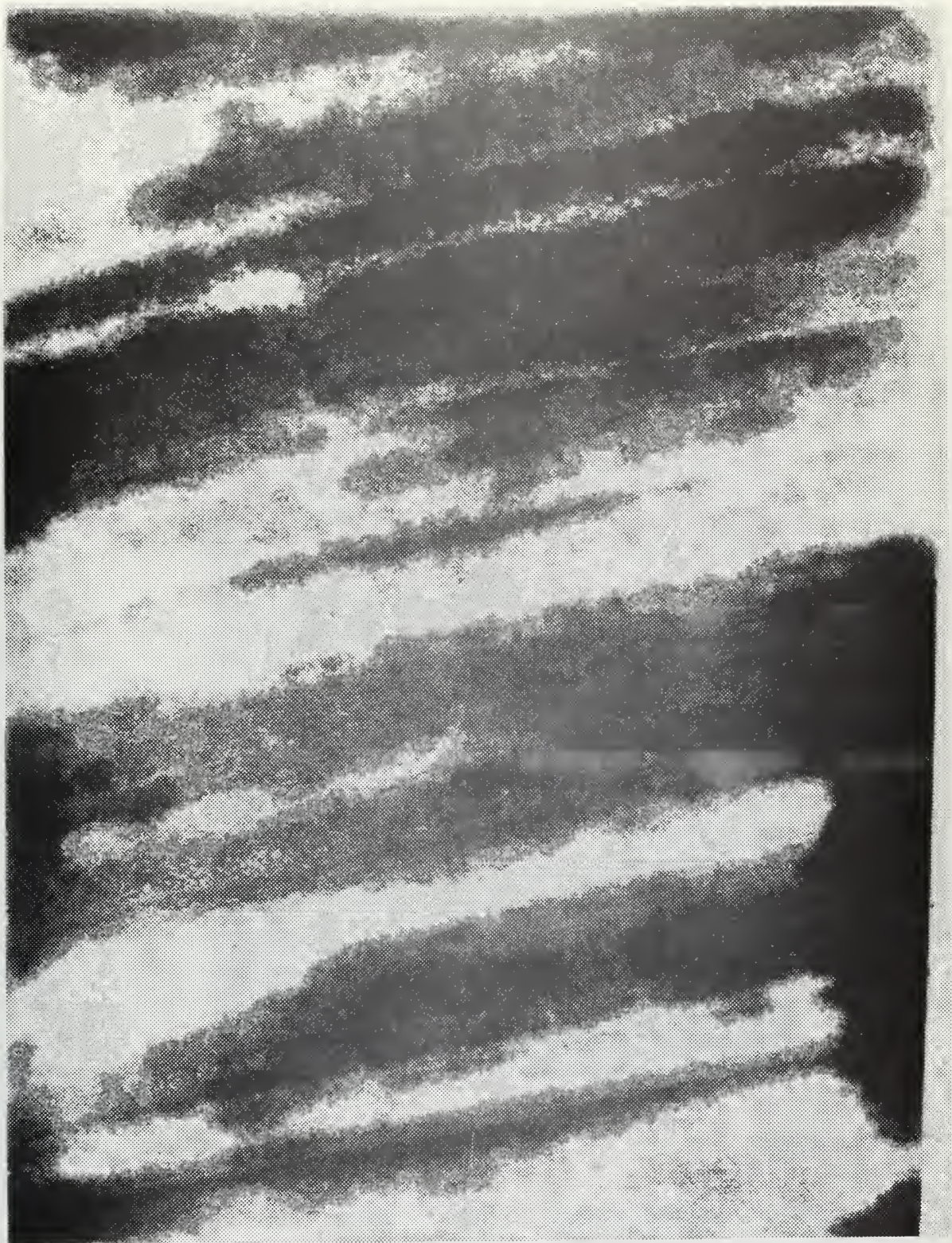
Figure 90. Radiograph of impregnation No. 10, Jan 23, 1971, Sequence No. 13 (actual size).



East

West

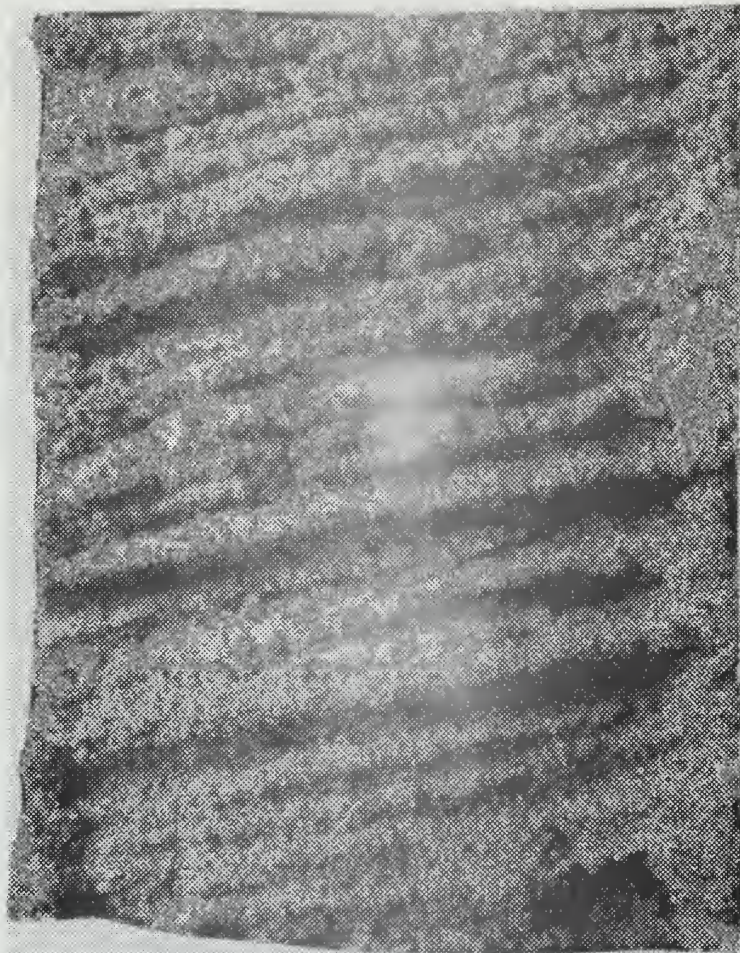
Figure 91. Photograph of impregnation No. 11, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

Figure 92. Radiograph of impregnation No. 11, Jan 23, 1971, Sequence No. 13 (actual size).



East

West

Figure 93. Photograph of impregnation No. 12, Jan 23, 1971, Sequence No. 13 (40% size reduction).



East

West

Figure 94. Radiograph of impregnation No. 12, Jan 23, 1971, Sequence No. 13 (actual size).

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13. ABSTRACT

A radiographic study was conducted on impregnated sand samples taken from beach cusps on Marina Beach, Monterey Bay, California, over a 7-month period from September 1970 to April 1971. The radiographs revealed much more structure than is discernable with the unaided eye in trenching or peeling. The microstructure found consisted of cross-lamination, rhythmic stratification, and distinct mineral layering. Migration of these cusps was studied by means of visual observations and time-lapse photography. Cyclic changes in the cusp profile were found to correspond with wave action and tidal influences. No simple relation between ocean action and cusp structure or development was evident.

| KEY WORDS | LINK A | | LINK B | | LINK C | |
|--------------|--------|----|--------|----|--------|----|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Monterey Bay | | | | | | |
| Beach | | | | | | |
| Cusp | | | | | | |
| Sand | | | | | | |
| Lamination | | | | | | |
| Impregnation | | | | | | |

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